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All communications should be addressed to the Editor.

No. 105. SEPTEMBER, 1919. VOL. XXIII.

Notices of the Royal Aëronautical Society.

The Syllabus.

The following lectures have been arranged for the Autumn Session. The lectures will, as in former years, be given at the Royal Society of Arts, John Street, Adelphi. The chair on all occasions will be taken at 8.0 p.m.:—

Wednesday, October 29th.—"The Static Head Turn Indicator for Aeroplanes," by Sir Horace Darwin, K.B.E., M.A., F.R.S. Chair to be taken by Brig.-Gen. R. K. Bagnall Wild, C.M.G., C.B.E., R.E.

Wednesday, November 12th.—"Some Physical and Psychical Effects of Altitude," by Chas. Atkin Swan, M.B., Ch.M., F.R.C.P. Chair to be taken by Sir W. Arbuthnot Lane, Bart., C.B., F.R.C.S.

Wednesday, November 26th.—"Some Kite Balloon Experiments," by Griffith Brewer. Chair to be taken by Brig.-Gen. E. M. Maitland, D.S.O.

Wednesday, December 10th.—"Under-Carriages," by J. D. North. Chair to be taken by Lieut.-Col. M. O'Gorman, C.B.

The Council.

At a special meeting of the Council held on July 29th, 1919, the Chairman reported that Mr. W. Barnard Faraday wished shortly to tender his resignation as Secretary of the Society, as he was desirous of resuming his practice at the Bar. It was resolved that the resignation be accepted with regret and that the zealous work done by Mr. Faraday for the Society deserved special consideration.

The Chairmanship.

At the meeting of Council, held on October 7th, 1919 (from the Council minutes):—

General Ruck then stated that he occupied that chair for the last time. He had great pleasure in inviting General Bagnall Wild to take his place and to acknowledge gratefully the great assistance he had always received from the Council, past and present, and from the staff of the Society.

General Bagnall Wild then took the chair. He acknowledged the honour

done him in electing him, but said he desired in all their names to express the very great indebtedness in which he and all of them stood to General Ruck for his long and unique services to the Society. He had, as a small token of their esteem, great pleasure in offering to General Ruck, on behalf of the past and present members and officials of the Council, a small silver model of an aeroplane.

The model was inscribed as follows:—

Silver Model of Fighter Aeroplane S.E.5.

Issued 1916 in the Great War.

Presented to

Major-General R. M. Ruck, C.B., C.M.G., R.E.,

as a farewell gift by his old colleagues, past and present, on the Council of the Royal Aëronautical Society, on which he served devotedly for eight years as Chairman, 1911-1919.

Major B. F. S. Baden-Powell.
Brig.-Gen. R. K. Bagnall Wild, C.M.G.
L. Bairstow, F.R.S.
A. E. Berriman.
Harris Booth.
Major F. H. Bramwell.
Griffith Brewer.
Lieut.-Col. W. Briggs, R.A.F.
Lieut.-Col. Alan H. Burgoyne, M.P.
Col. A. D. Carden.
Lieut.-Col. Cave-Browne-Cave.
Sir Mackenzie Chalmers.
E. P. Frost, J.P., D.L.
Sir Robert Hadfield, F.R.S.
F. Handley Page.
Brig.-Gen. Sir Capel Holden, F.R.S.
G. Holt Thomas.
Lieut.-Col. T. O'B. Hubbard.
Maj.-Gen. E. M. Maitland, D.S.O.
Lieut.-Col. F. K. McClean.
W. O. Manning.
Lieut.-Col. Ogilvie, C.B.E.
Lieut.-Col. M. O'Gorman, C.B., R.A.F.
Col. H. E. Rawson.
Major R. V. Southwell.
Dr. T. E. Stanton, F.R.S.
Maj.-Gen. Sir F. H. Sykes, K.C.M.G.
Capt. A. P. Thurston, D.Sc.
Lieut.-Col. H. T. Tizard.
Dr. R. Mullineux Walmsley.
H. White Smith.
W. Barnard Faraday (Secretary).
Olive St. Barbe (Assistant Secretary).

General Ruck suitably replied.

The Secretaryship.

The Council invite applications from the Society for the post of Secretary, which will shortly become vacant.

Applications should reach the Secretary before the 31st October, 1919.

Applicants should state their war service, membership grade, secretarial and technical qualifications, and the rate of pay required.

METAL CONSTRUCTION OF AIRCRAFT.

BY A. P. THURSTON, D.SC., F.R.AË.S., F.R.MET.S., M.I.A.E.

This war has been fought with machines made of wood, a most unsatisfactory material from a constructional point of view. Wood warps and cracks; is unsuitable for tropical climates; splinters easily in a crash; is liable to transfix the aviators; is non-homogeneous; uncertain in strength and weight; weakens rapidly when exposed to moisture; and is not produced in any quantity in this country.

On the other hand, metal does not splinter; it is much safer in a crash, the members hanging together and forming a shield to protect the aviators; its properties are known to a fine degree and may be relied upon; it can be produced in immense quantities; and, moreover, metal members after breaking can still carry a considerable load. Many lives have already been saved by the use of metal bodies.

A year ago over 1,000 all-metal machines had been used with success in the allied fighting line, but not one had been made in this country. Had the war extended into this year, however, a prodigious number of machines, made of steel and duralumin, exquisitely designed for their functions, would have been produced, to swamp the enemy beyond all hope—so great are our still undeveloped resources. The armistice stopped this.

It will probably take ten or more years now before metal construction will have reached the stage of development that it would have reached in ten months under war conditions. It is hoped by drawing public attention to the problem, and by placing information at the disposal of firms interested, to hasten the development of this important industry. Our future as a nation depends so much upon our position in the air that we cannot afford to neglect so important a subject. Ultimately all our large machines will be of metal and it is thought that no aeronautical firm can afford to neglect metal construction.

Heretofore the problem has been tackled by manufacturers largely from patriotic reasons. It is a pleasure to pay a tribute to the patriotism and energy which these enterprising manufacturers brought into the struggle. Almost without exception there has been no dog in the manger business in their policy. In many cases they have passed on generously exclusive information and trade secrets to hated rivals in order to assist them to beat the common enemy. That is the spirit to carry into peace conditions. While our manufacturers are animated by that spirit we have little to fear from foreign competition, provided always that this spirit is fostered and encouraged by wise and unselfish Government officials.

With regard to metal construction of aircraft, it may be argued that metal is too heavy to be used to construct efficient flying machines. The same argument was used in the early days of iron vessels; now wood is used only to construct small craft, and all large vessels are constructed of steel. It will be shown later that steel and duralumin are stronger than wood, weight for weight, and that the vital members of our flying machines can be, and have been, made lighter and stronger in metal than in wood. As a matter of fact, the strongest flying machine yet made by any Power, and loaded until broken, is a metal Avro machine constructed by Messrs. Vickers, and this machine is lighter than the standard wooden machine.

The advantages of metal construction are not confined to greater strength, lightness, reliability, and ultimate cheapness. Its use will enable many new

developments to be made in the actual design of aircraft. Thus, flying machines with variable camber wings will have great advantages for commercial purposes over the common design, in that these machines may be landed at a slower speed than any other type. Those who have had much experience of cross-country work and forced landings will appreciate this. Many attempts have been made to construct variable camber machines and these machines have been successfully flown. Some of the greatest constructional difficulties encountered will be obviated by adopting metal construction.

It was the author's intention when he took up the subject to deal fully with the whole problem, including methods of calculation. He soon found, however, that he would be compelled, from considerations of time alone, to limit his paper to a small portion of the subject.

The design of aircraft resolves itself into two more or less distinct problems, namely, the aerodynamical and the structural design. The aerodynamical design comprises the determination of the correct areas, shapes and dispositions of the various surfaces to obtain the best performances with the required loads and horse-power available—the structural design consists in providing members to carry the loads on the various surfaces with the required factor of safety. The most efficient structural design is one in which the required strength is obtained with the minimum weight of structure and the maximum ease and cheapness of production. Further requirements of an efficient design are durability under varied weather conditions, ease of repair and safety in a crash.

Heretofore, with a few notable exceptions, the vital members of the aircraft structure have been made of wood. The weight and strength of specimens from the same species of wood differ greatly. Spars for one type of machine were found to vary in weight from 6½ lbs. to 16 lbs., and the strength varied in practically the same proportion. In addition, the strength decreases with the amount of moisture absorbed. Thus, the strength of spruce in compression decreases 230 lbs. per sq. inch per 1% of moisture between 10% and 25% moisture. Wooden machines sand tested under the very favourable conditions of a dry workshop therefore showed a much greater strength than in the field. A sodden machine in the tropics may have only half the strength of the same machine when tested in the workshop at home. Moreover, owing to the disposition of wood to warp or split, particularly under tropical conditions, a wooden machine quickly gets out of truth and requires trueing up. Wooden wings deflect a great deal under load, thus making it impossible to keep all portions at an efficient angle of incidence. For instance, in a single bay wooden machine under load it was found that the angle of incidence changed 1° under the struts, while in the middle of the bay the angle of incidence changed 2½°. As this machine flew with an angle of incidence of not more than 1° it follows that some parts of the wing were lifting much more than other parts; moreover, the maximum loads were applied in the least favourable place, namely, in the middle of the bay.

From these considerations it follows that there is a strong argument in favour of metal construction if it can be efficiently and cheaply utilised.

We are an engineering nation with vast mineral resources and practically no timber, and our knowledge of high grade steels is superior to that of any other nation.

It is therefore sound policy in view of the vital importance of aeronautics to our safety as a nation that we should spend large sums in developing metal aircraft. At no distant date we may expect to see flying machines of not less than 100,000 to 200,000 lbs. and metal is the only substance from which such machines can be satisfactorily constructed. Metal machines have now been thoroughly tested in the air. They have been spun, rolled and looped and sand tested.

Basic Principles.

The metals which are immediately available for metal construction are steel and duralumin, other alloys should be available shortly.

The specific gravity of good dry spruce, grade A = .45.
,, ,, steel ... ... = 7.8.
,, ,, duralumin ... ... = 2.8.

Young's modulus in bending for all steels approx. = 13,600 tons sq. in.
,, ,, ,, duralumin ,, = 5,500 ,, ,,
,, ,, ,, spruce, A ,, = 715 ,, ,,

Hence, steel is 17 times heavier than good spruce
and duralumin is 6 ,, ,, ,, ,,

The modulus is of course less in tension.

The strength of spruce in combined bending and end load cannot be assumed greater than 5,500 lbs. sq. in. or 2.45 tons sq. in., and the pure bending test should never be used for wood. Grave errors have resulted during the war owing to pure bending tests only being taken.

It follows that steel of 42 tons per sq. inch or duralumin of 15 tons per sq. inch are equal in pure bending, weight for weight, to grade A spruce, providing the full strength of the material can be developed.

Now the strength of a long strut or spar under combined bending and end load is governed by the modulus of elasticity.

The strength of a long strut with free ends being given by Euler's formula $\pi^2 EI/l^2$.

It follows that steel struts are, weight for weight, 1.1 times as strong as spruce, and that duralumin struts are 1.2 times as strong as spruce, provided the full strength of the metal is developed. These figures relate to the best wood obtainable under peace conditions, but they are much more favourable to metal when compared with wood available under war conditions.

Thus, the specific gravity of dry Oregon pine or Douglas spruce, which we have been compelled to use in large quantities, is 0.51.

The combined end load and transverse strength or bending strength of grade B timber is 4,500 lbs. per sq. in. or 2 tons per sq. in.

The modulus of elasticity of grade B timber is 625 tons per sq. in.

Therefore steel is 15 times heavier than grade B Oregon pine, and duralumin is $5\frac{1}{2}$ times heavier than grade B Oregon pine. Hence, steel of 30 tons per square inch or duralumin of 11 tons per square inch are equal, weight for weight, in pure bending to grade B Oregon pine, provided the full strength of the material can be developed. Further, steel struts are, weight for weight, 1.4 times as strong as grade B Oregon pine, and duralumin struts are 1.6 times as strong as grade B Oregon pine. Moreover, since the deflection of a beam under load is proportional to the modulus of elasticity and the end load in a beam introduces an additional bending moment equal to the product of end load and deflection it follows that the above figures are capable of being improved upon, provided always that such a design can be obtained and that the full strength of metal can be developed.

Metal construction has the further advantage that the metal may be disposed at a greater average distance from the neutral axis.

It may be argued, since the modulus of elasticity of all grades of steel is approximately the same, that the grade of steel to be used in struts is of no importance. This is not so in fact, because with mild steels small local damage causes local failure, whereas with higher grade steel local damage is of minor importance.

Local Failure.

The metal used in the construction of metal aeroplanes must be extremely thin if it is to compete in weight with wood. The most useful thicknesses for steel have been found to be .015in., .018in. and .022in.

Duralumin has the advantage over steel in that it is three times thicker, weight for weight. The chief difficulty with thin metal structures is local failure due to local flexure before the full strength of the material has been developed.

A preliminary series of tests were made by Major Wylie on square tubes having flat sides 1⅜in. wide which were fifty times the thickness of the metal. The tube was heat treated so as to raise the elastic limit of the material to above 80 tons per square inch, but when tested by bending, the side in compression formed transverse corrugations at a stress of 25 tons per square inch, and these corrugations increased with increasing load, and finally caused failure at a stress of about 40 tons per square inch.

When tested in compression the tube failed completely at about 25 tons per square inch as soon as the corrugations appeared.

Further tests on circular tubes of the same thickness and of diameters varying from 1⅜in. up to over 2in. were also made, and in all cases the circular tubes developed the full strength of the material. A 1⅜in. × 22 gauge tube did not collapse until a stress of over 110 tons per square inch had been reached, and then failed suddenly at a slight dent. A tube having a diameter of over 2in. and a thickness of .01 of its diameter, which is considerably less than 22 gauge, did not fail until a stress of 100 tons per square inch had been reached, and then failed in tension. It is evident, therefore, that curved surfaces must be used instead of flat surfaces.

From tests which have been made it appears that the radius of curvature should never be more than twenty times the thickness of the metal. This is unlikely to put any limitation on good design and will ensure the section standing up to the maximum strength of the material without failing, and make it capable of taking a fair amount of punishment from local damage.

A series of designs of spars and struts in which the principle of longitudinal corrugation has been applied will be shown later.

Before proceeding to consider these designs it is desirable to set forth particulars of the materials of construction available.

Materials. Steel Strip.

Thin steel strip is produced by cold rolling, as it is not economical to roll material in the hot state to less than 17 or 18 gauge.

The hot rolled strip is usually first pickled and then cold rolled to the thickness desired. As the metal is reduced in thickness it is hardened, and the tensile strength and yield point increased, and a point may be reached where the hardness is so great that it must be removed by annealing before further reduction can be made.

With a .3 carbon steel a reduction of more than 40% by cold rolling after annealing makes the strip too brittle. A 0.1% carbon steel may be reduced to a quarter its thickness before annealing is necessary, whereas a .8% carbon steel can only be given a slight reduction in thickness without annealing. This makes the process of cold rolling costly and laborious—.3% to .4% carbon steel appears therefore to be the most suitable quality in which to obtain large output with good strength.

By cold rolling a .3 to .35 carbon steel the tensile strength and yield point may be increased up to about 65 tons per square inch with practically no ductility. This renders the strip unsuitable for rolling into suitable sections.

If, however, the strip is tempered or "blued" for 15 or 20 minutes at any temperature between 0° and 450° C., the ductility may be increased to any desired amount according to the temperature, and the maximum breaking stress and yield point do not fall to that of the original cold worked figures until a temperature of 425° to 450° C. is reached.

Usually blueing for 20 minutes at 400° to 450° can be relied on to increase the ultimate and yield strength by 5 tons per square inch and the elongation from practically nothing to about 7%.

This is a remarkable property of steel which was first discovered in connection with tubes and afterwards applied to steel strip.

One process of manufacture is therefore by cold rolling and "blueing" simple carbon steels. The process of rolling develops a grain in the material which cannot be removed even by complete annealing; steel strip is therefore unsuitable for bending or rolling into sharp angles and all strip steel designs should be formed of easy and continuous curves or corrugations. This is a second reason for longitudinal corrugations in design.

A second process of manufacturing steel strip is by continuous quenching and annealing low and medium carbon steel strip. The response to this form of heat treatment is very much greater in thin strip than in ordinary sections. There are several modifications of this process. In one process the steel strip passes continuously through a furnace and the red hot strip is quenched by running through an oil bath. The quenched strip then runs through a lead bath and is tempered. In another process it is quenched by running between cast iron or steel dies through which water is circulating and is afterwards tempered in a gas furnace. In both the oil quenching and lead tempering process and the die hardening and gas tempering process care must be taken to cool the strip after being tempered before winding on a coil, otherwise the heat accumulated and the strength and ductility of the strip at different ends of the coil varies considerably. Some of the best results have been obtained with rejected corset steel. A coil of steel containing about .32% carbon, oil quenched, hardened outright and tempered at 200° C., had a strength of 115 tons per square inch with quite moderately good ductility, while after tempering at 250° the strength was 110 tons per square inch, the yield 90 tons per square inch, and the ductility was sufficient when bent along the grain to enable it to be rolled into a standard corrugated flange. Further tempering of this same strip at 450° C. reduced the strength to about 70 tons ultimate and 65 tons yield, and induced sufficient ductility in the material to enable it to be flattened on itself either way of the grain so that this metal was quite capable of withstanding being pressed into ribs.

The effects of cold rolling, blueing, quenching and tempering similar steels to the above is set forth in an interesting monograph, Appendix I., contributed by Mr. G. Glenn, of Messrs. Arthur Lee and Sons, Ltd.

The third process, which has yielded excellent results, has been developed by Messrs. Kayser, Ellison and Co., Ltd. This process consists in hardening and tempering by a special process alloy steel strip. The resulting product is scoured by a special process and can be welded, punched, rolled and bent longitudinally and laterally without further heat treatment.

This steel should be tempered either below 150° C. or above 450° C. if durability and capacity to resist shock and vibration are required. This remarkable phenomenon is set forth in the interesting monograph, Appendix II., by Mr. Henshaw, of Kayser, Ellison. Between these temperatures the Izod impact test gives a low figure. Further properties of this type of steel are set forth in Mr. Mackinder's monograph, Appendix III. It is a pleasure to pay a tribute to the patriotic way in which Mr. Kayser, of Kayser, Ellison and Co., Ltd., together with the firms of Arthur Lee and Co., Ltd., and The Effingham Steel Co., and

other manufacturers of Sheffield and district have tackled and solved successfully the problem of the evolution of metal strip suitable for aircraft construction.

The strength of metal constructions appears to be governed more by the yield point than by the ultimate strength, hence attention should be paid to obtaining a good yield point. Straight steel strip can now be obtained up to 5in. wide, having yield points of 100 tons, 80 tons, 60 tons, or 40 tons.

In ordering strip care should be taken to order the exact width required, since the process of splitting the strip invariably gives it a curve which can only be corrected by additional heat treatment.

Duralumin.

The second material available for metal construction is duralumin. This has many advantages over steel and a few disadvantages. Duralumin being three times lighter than steel it follows that the various members may be, weight for weight, three times thicker than steel members. Hence the difficulty in overcoming local failure due to local flexure is greatly reduced. Nevertheless, the perfection of a design can only be discovered by constructing it in steel, and it is thought that duralumin designs will be improved by adopting the principles which have proved to be the only feasible ones in steel construction.

A prejudice appears to exist in certain quarters against duralumin owing to the fear of corrosion. It should be stated that duralumin, unlike aluminium, is not acted upon by sea water, or affected by atmospheric influences, and experience in connection with airship work shows that duralumin, if properly varnished, is not affected by corrosion under ordinary conditions of service.

Nearly every case of corrosion so far experienced in actual practice has been traced back to incorrect heat treatment, or to cold working after heat treatment.

The heat treatment of duralumin instead of being a disadvantage, as is often supposed, is in actual point of fact of the greatest assistance in the practical working of the metal. This heat treatment is carried out by placing the member to be treated in a bath containing a mixture of potassium and sodium nitrates heated to a temperature of 480° C. In practice there is a fairly wide margin of temperature so long as 500° C. is not exceeded, in which case there is danger of the metal being burnt and reduced to aluminium.

The parts should be left in the bath long enough to be heated uniformly to the temperature of the bath, the actual times allowed being five minutes in the case of small units up to several hours in the case of 3in. bar. There is no danger in leaving it in the bath too long, providing the actual temperature of 500° is not exceeded.

At the end of this time the article is removed from the bath and quenched out in water or non-acid oil.

Immediately after heat treatment the metal is found to be in a very soft and plastic condition and it may be pressed, forged, bent to the smallest radius, or in the case of drawn sections which have warped with the quenching, straightened without any fear of damaging the metal. The metal now commences of itself to harden up, and in about an hour's time has reached about 26 tons tensile strength, with an elongation of about 15%.

This process of hardening continues for a very long period, the strength slightly increasing at the expense of the elongation.

Heating duralumin to 300° C. and then quenching out anneals the metal and it can then be worked in any way desired. In order to give it back its strength it is necessary to heat treat it at 480° C., as explained above.

In practice it is usual to anneal any duralumin part if a number of operations have to be performed, and on the other hand to heat treat before final operation

if this is not of too prolonged a nature, taking advantage of its abnormal condition immediately after heat treatment.

An actual example of the value of this property of duralumin in slowly hardening up after heat treatment occurs when duralumin is used for rivets. If an attempt were made to rivet these up in the ordinary hard condition they would crack badly. By heat treating them, however, and using them immediately after this, a perfect job may be made while they are soft, and within a very short time afterwards they have hardened up to their full strength.

If duralumin in the ordinary hard condition is bent to a small radius, there is, as would be expected, a probability of incipient cracks developing on the surface of the metal at the bend. These cracks are the places where the corrosion begins. If the metal was properly heat treated before such bending, no injury would be caused to the surface of the metal, and no trouble would be experienced from corrosion. Nearly the whole of the prejudice against the use of duralumin is due to ignorance as to its properties with and without heat treatment. Sections cannot conveniently be drawn thicker than .2in. Above this thickness the sections are extruded. It is advisable to use only solid drawn sections for constructional purposes and designs should accordingly be modified to meet the limitations in the material.

Constructional Designs.

Having now described some of the properties of the materials available for metal construction it remains to describe methods of utilising these materials in an efficient and practical way. The structure of an aeroplane may be divided into two main portions: (*a*) The vital members, such as spars, struts, longerons and lift wires, and (*b*) the members giving form or bulk, such as ribs, ailerons, elevators, etc. The latter members are not stressed to the maximum limit in the same way as the vital members, and present no great difficulty in competing with wood. Thus, metal ailerons have been made and tested which were 40% lighter and 60% stronger than the wooden ailerons they were designed to replace. Improvements in design are to be looked for only in increasing the cheapness of manufacture.

With regard to the vital members the problem is far different and here all our ingenuity and knowledge is required.

Metal designs are required for three main types of machine: (*a*) Small machines up to 3,000 lbs.; (*b*) intermediate machines from 10,000 to 15,000 lbs.; and (*c*) large machines of from 30,000 to 200,000 lbs.

The largest members in a machine are the wing spars and these present the greatest difficulties in construction—the next largest members are the struts. As it is impossible to deal with the whole vast problem of metal construction in one paper it is proposed to limit the description to these members for the above types.

Rudge Spars.

A section of the Rudge spar, developed from designs courteously placed at the firm's disposal by Lieutenant-Commander H. Wylie, and suitable for the Avro machine, is shown in Fig. 1.

In this spar an effective strength of 80 tons per square inch in the steel is utilised. To meet the weight requirements the thickness of the flange strip is reduced to 1% of its width, while the thickness of the web strip is reduced to $\frac{1}{2}$% of its width. To prevent local failure the strips have been formed into longitudinal corrugations, the radius of each corrugation being from 30 to 100 times the thickness of the metal, a smaller radius being used when the highest compressive stresses are to be withstood. These corrugations are so effective that

the Rudge spar shown has developed a compressive stress of 83 tons per square inch in the flange, while the webs have remained intact under a shear stress of about 30 tons per square inch.

FIG. 1.

When tested at the Royal Aircraft Establishment it was found that this spar is 10% lighter and 5% stronger than the wooden spar it was designed to replace.

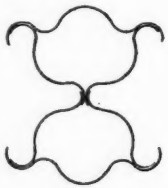


FIG. 2.

Fig. 2 shows a modification of the Rudge spar for intermediate type machines.

The first step is to deepen the central corrugations in the webs so that they meet together, thus forming the section into two tubular units. Each web is formed of two pieces joined together at the neutral line. This is necessary in view of the limited width of strip available. The free ends of the flange are turned inwards so that the maximum stress is not developed at the free edge. This considerably increases the strength of the flange.

The best disposition of the free ends of the strip constitutes one of the problems of metal construction.

The solution lies in placing the free ends in position where they will be stressed as little as possible. Failing this they must be locally supported or strengthened if the full strength of the metal is to be developed without local failure. The Huns solved this difficulty very well with their Zeppelin bracing.

FIG. 3.

They stamped the diagonal bracing members to the section shown in Fig. 3. Thus, the free ends AB were on the neutral line and were not stressed when the member was in compression as a strut.

Fig. 4 shows a modification of the Rudge spar for a larger machine of the intermediate type or a small machine of the large type.

With this type of spar the metal must be increased in thickness to retain sufficient stability. These derived sections are obviously weak about the waist and support must be given by cross frames, or formers, which suitably occur at

each rib. With the addition of these frames the section is made stiff in all directions even when the strip composing it is of extreme thinness relative to its width. The flanges are supported in the middle by extending the web into contact with the inner surface.

FIG. 4.

Fig. 5 shows a modification of Fig. 1. The depth of the spar may be readily altered by varying the depth of the central corrugations of the webs, the minimum depth being obtained where the corrugations meet in the centre. In the event of the corrugations not meeting, as in Fig. 5, it is necessary to join the webs together at intervals by a cross tubular member riveted to each.

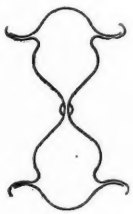


FIG. 5.

The above designs are adapted to be riveted together either by hand or by machine.

Dunlop Spars.

Several designs have been adopted to utilise spot or strip welding—this dispenses with the difficult, and at present somewhat expensive, process of riveting.

One such design, known as the Dunlop single spar, is shown in Fig. 6.

Three coils of strip of the required width are mounted on the rolling machine. After passing through the banks of rolls each strip emerges of the required shape and passes through guides which hold the strips while they are passed between two pairs of copper discs at A and B, which are the terminals of an electric circuit. A powerful current then passes from one disc to the other through the steel strip. The resistance offered by the strip to the passage of this current is sufficient to raise the strip to a melting temperature. After leaving the discs the ends of the

strip are firmly incorporated together at the points AB. The spar emerges complete from the machine at the rate of 9 feet per minute.

This spar is almost the same in section as Fig. 4 except that each tubular unit is rolled from one strip instead of being built up from three strips. This feature is advantageous in many ways, but limits the size of the tubular unit to about two inches wide on account of the difficulty of obtaining and working up high tensile strips wider than about six inches.

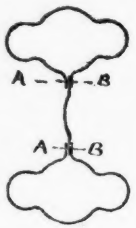


FIG. 6.

One great advantage of the Dunlop type of boom is the absence of the projecting ledges provided on the previous spars for connecting the component strips together. These ledges are liable to buckle when high longitudinal compression stresses are developed in them, even if they be curved throughout and rolled round on the edges as shown in the illustrations.

FIG. 7.

Fig. 7 illustrates a section known as the double Dunlop spar. The edges of two strips are rolled into tubes and strip welded, the intermediate portions of the strip being longitudinally corrugated. The formed strips are placed back to back and connected together by spot welding. This spar is in effect two bicycle rims placed back to back and connected together at the centre. Similarly to the Dunlop single spar it requires to be supported by frames or formers at intervals to prevent the individual booms from bending as struts transverse to the web. The formers may conveniently be introduced at each rib. It has been found from tests that the distance between frames or formers should not exceed 60 times the radius of gyration of the booms. Hence, for this spar the booms require to be about one inch wide.

This spar can be made as light as .5 lbs. per foot run and develops the same strength as a wooden spar of from .65 to .85 lbs. per foot run. This type of construction is the cheapest and simplest yet developed.

In the spar designs shown the strips run continuously throughout, no holes being cut to lighten the sections. This continuity is a feature and has great advantages, for it has been found in tests that destroying the continuity weakens the spar considerably. Lightness can be obtained with less sacrifice of strength by reducing the thickness and increasing the curvature of sections. From experience it would appear that spars with continuous webs can be made as light as with any system of trussing, and for a given weight will be considerably stronger and more rigid.

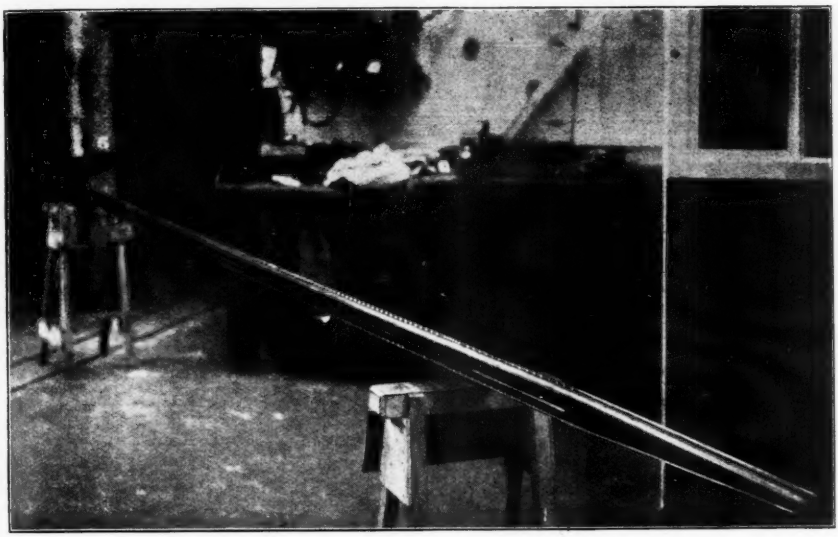


FIG. 8.

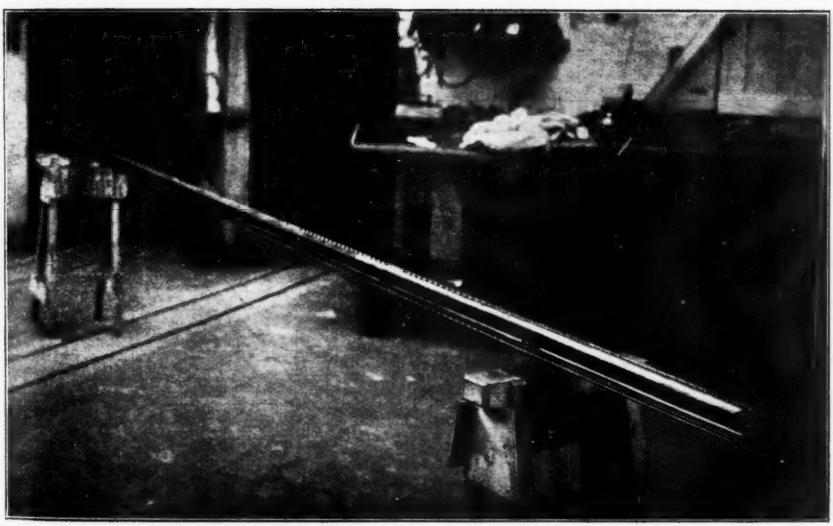


FIG. 9.

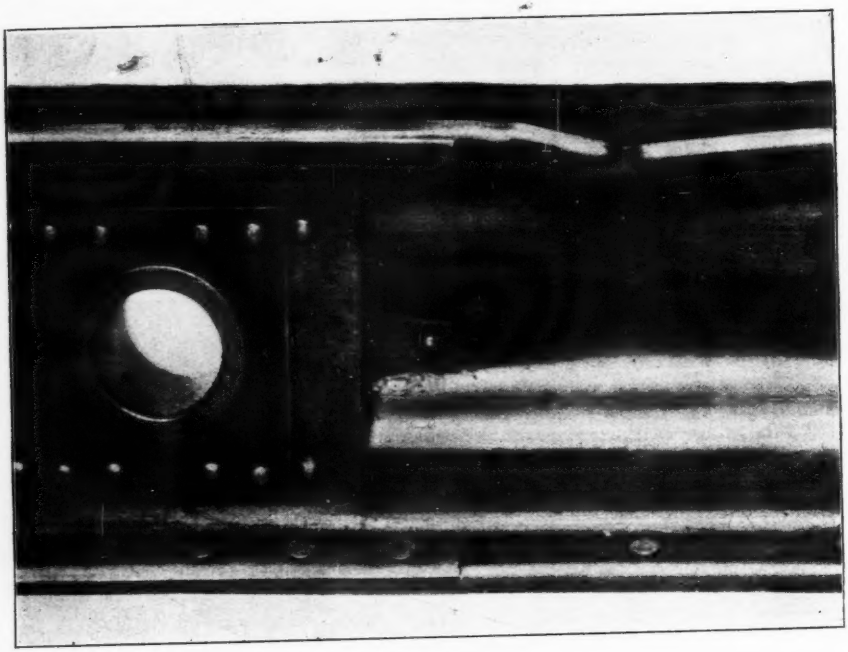


FIG. 10.

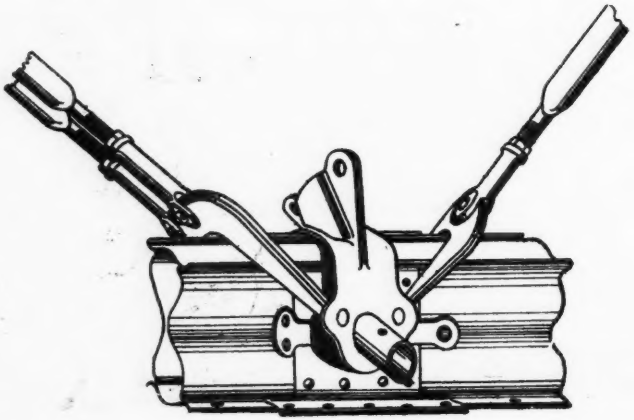


FIG. 11.

A second feature in these designs is the absence of rivets and other means of connection along the lines of maximum stress.

In the Rudge spar, for instance, the maximum possible tensile stress along the line of rivets is about 85% of the maximum stress in the flange. In the case of the Dunlop spars it is much less.

A third and perhaps the most important feature is that all the metal in the section, except the cross frames of the ribs, is taking its share of the load, so that even if the average stress over the area is less than is developed in the longitudinal parts of lattice spars, the absence of bracing pieces more than compensates for the lower failing stress of the flanges.

Figs. 8 to 10 show photographs of a Rudge spar and specimens of complete Rudge and Dunlop spars are on the table.

Methods of Attaching Fittings.

Another problem of metal construction, presenting in fact almost as much difficulty as the actual design, is the attachment and design of fittings. Fittings and reinforcements are required whenever a load is applied in order to distribute that load. Thus, spars should be reinforced with boxes at the inner ends to distribute local bending moment due to inequalities of end loading. In addition, all fittings should preferably be attached to the neutral line.

Fig. 11 shows a method of doing this for the Rudge spar. The webs are reinforced by plates which carry a short tube. Another tube acting as a compression strut is passed through the hole; to this tube is pivoted a forked member carrying the strut, and links for the lift and anti-lift wires. By this means all the forces cut one another on the neutral line of the spar, thus avoiding offset bending moments and simplifying the calculations of the strength of this structure.

Figs. 12 to 14 show photographs of modified fittings of the Rudge spars.

In this case the lift and anti-lift wires are pivoted to the central tube. The photographs are self explanatory.

Boulton and Paul Spars.

Very interesting experiments have been carried out by Boulton and Paul with a modified type of Rudge spar shown in Fig. 15.

The flange is provided with two corrugations having flat horizontal edges. The centre portions of the webs are stamped with flanged holes as in the early Rudge spars, and are provided with longitudinal corrugations above and below these holes. The edges of the web are doubled over to embrace the flat edges of the flanges, and the spar is completed by suitably placed rivets. This spar is extremely efficient under test. A spar made from material whose ultimate tensile strength was given by the manufacturers as 40 tons, developed a stress of 43.5 tons per square inch in the flanges before failure. It is claimed that this spar is 12% lighter than a spruce spar and will sustain 70% increased bending moment. The first specimens were rolled from 40 ton steel .018in. thick. Flanges of steel with higher tensile strength are now used, and the ultimate strength of the flanges is developed simultaneously with the ultimate shear stress of the webs.

Fig. 16 shows an early specimen in shackles, taken after testing to destruction. The flange of this specimen is provided with a single shallow corrugation and failed before the full strength of the specimen had been developed. The dent in the flange shows where the spar failed.

Fig. 17 shows a photograph of a complete pair of wings provided with Boulton and Paul spars.

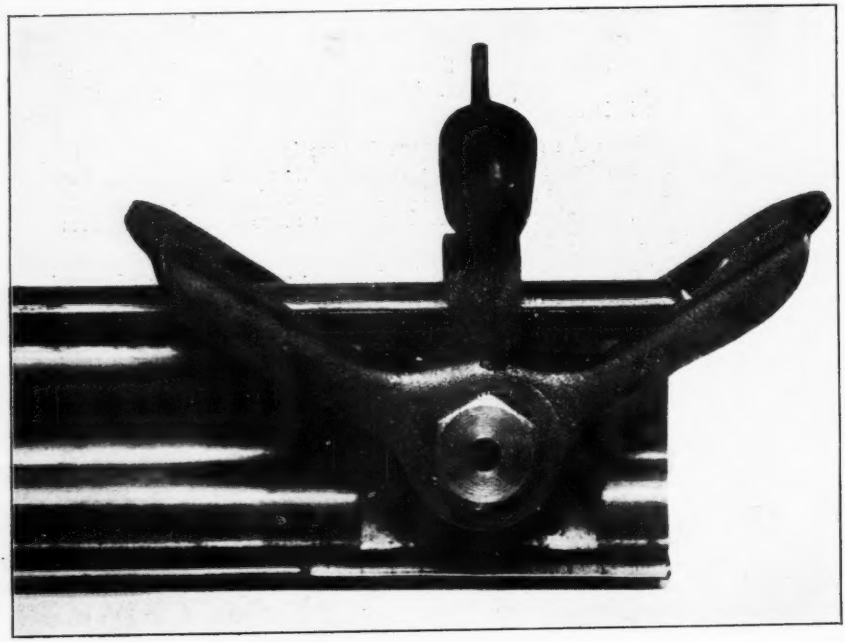


FIG. 12.

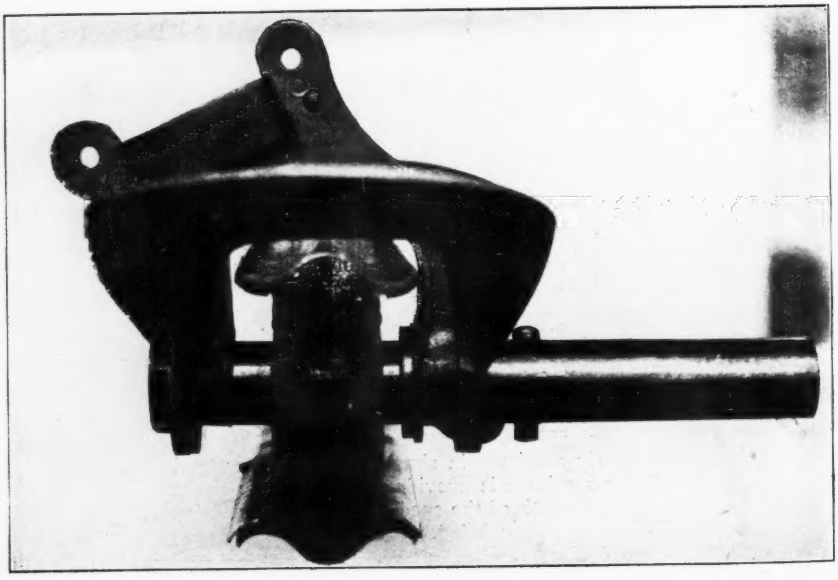


FIG. 13.

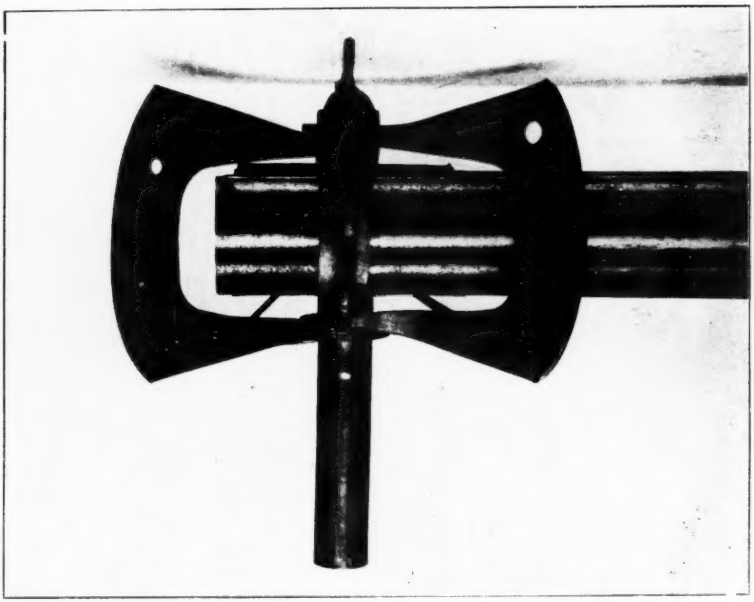


FIG. 14.

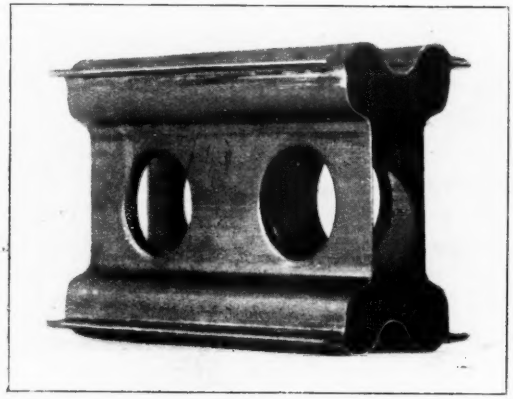


FIG. 15.

FIG. 16.

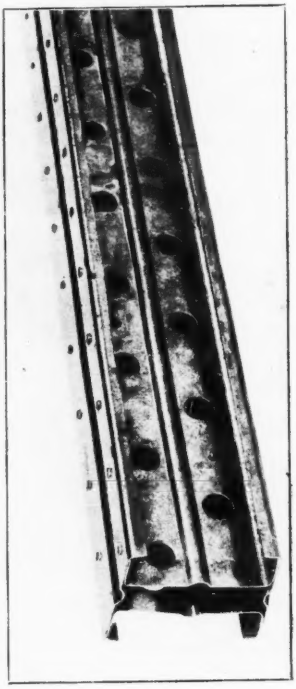


FIG. 18.

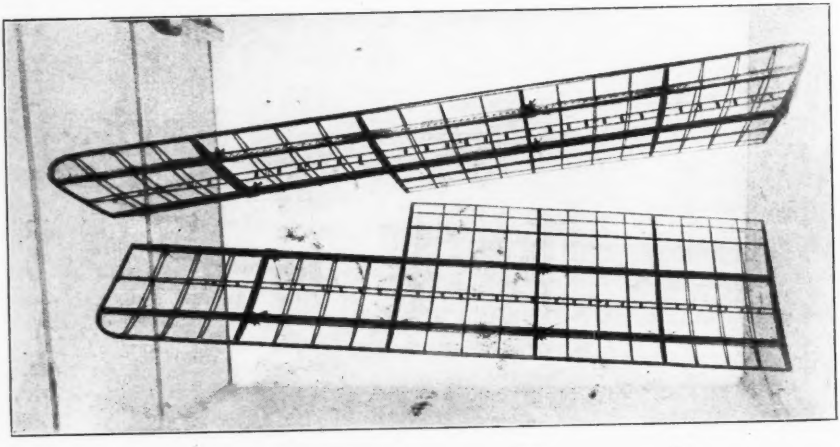


FIG. 17.

Humber Spars.

The spars previously described have been made from rolled strip. A second alternative is to construct spars from metal sheet which can be obtained in lengths up to 10ft. from firms such as Sankey's and Firth's.

Valuable and useful work has been carried out in developing this form of construction by Colonel J. A. Cole, Mr. Nibblet, and Mr. Horsfield, of Humber's, Ltd. An original design from which this firm's design was developed was very courteously placed at their disposal by Captain Green, of Siddeley Deasy.

A drawback to all the designs heretofore described is the difficulty in applying them to existing machines without re-designing the fittings.

Messrs. Humber have produced a design which solves this difficulty, and they constructed a metal machine in record time. The first section, Fig. 18, was made of 25 gauge 31 ton steel sheet for both flange and web. The width of the flange was two inches and a stiffening bead or longitudinal corrugation was rolled in the centre of the flange throughout its length. The web was lightened by circular holes punched on either side of a longitudinal bead or corrugation in the centre of the web and slightly smaller than the flange. This section is the same in all over-all dimensions as the standard Avro spar. The spar was made up of four lengths joined together by staggered lap joints, three of these lengths being identical, the fourth being tapered to suit the outer extremity of the wing. The webs and flanges were pressed to shape in a stamping machine.

The ultimate section decided on was similar to the above but of 35 ton steel with the flange and web of 26 gauge.

Fig. 19 shows a photo of the first plane built up on metal spars and tested at Farnborough, where it successfully withstood the required load.

Fig. 20 shows in detail the method of attaching the internal bracing and strut sockets and wiring plates to this wing. Standard Avro fittings are used throughout. The interplane strut fittings are raised from the spar by means of a very light steel box. The spar is stiffened to take internal bracing by means of a pressed steel cross transmitting the strain radially from the transverse bolt to the flanges and webs of the spar. The spar itself is stiffened to take torsional strain by means of aluminium distance pieces, the webs being connected by means of aluminium rivets passing through the distance pieces. The thrust of the interplane struts is taken on an aluminium pillar passing radially through the spar directly under the strut, the pillar being pierced by the transverse bolt which passes through pressed steel crosses. These crosses distribute the load over a large area of the spar.

Figs. 21 and 22 show another method of attaching the fittings which is self explanatory. The specimen has been tested to destruction and shows the failure of the flange in the centre.

Struts.

The solution of the strut problem is much simpler than that of the metal spar.

There are several principles which must be kept in mind in tackling the problem. Since the external shape must be such as to offer the minimum head resistance, we are limited to a streamline shape. If a steel tube is used it must obviously be provided with fairing back and front, which does not contribute greatly to the strength, but adds considerably to the weight; moreover, steel tubes of high quality are expensive. It follows that steel tubes are not the best construction for this purpose except in non-exposed places, where streamlining and diameter are of no consequence. If the exterior of the metal strut is to be streamline, the moment of inertia about the minor axis will be much greater than about the major axis. This does not lead to an efficient disposition of the metal.

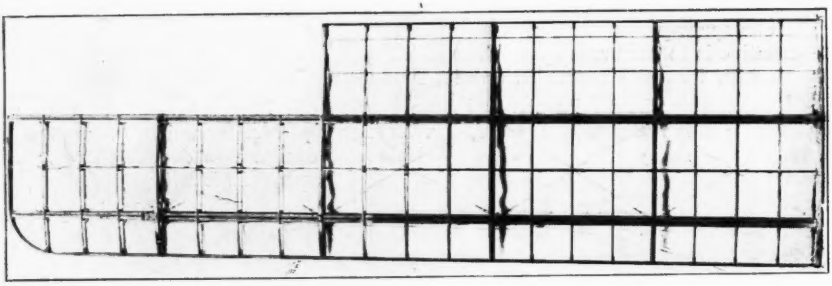


FIG. 19.

FIG. 20.

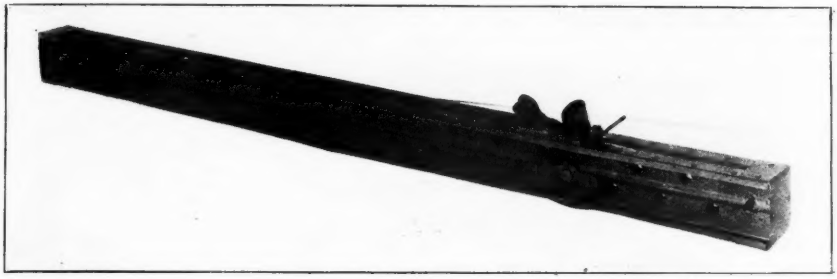


FIG. 21.

Moreover, the front and rear edges are sharply curved and hence self-supporting, whereas the sides are only slightly curved. The principle therefore to strive after is the provision of more metal at the sides and rigid supports for the sides.

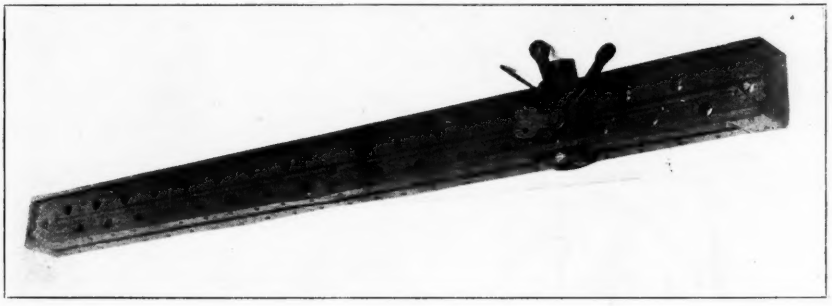


FIG. 22.

This problem has been very successfully solved by C. A. Llewelyn Roberts, of the Birmingham Guild, and by Messrs. Sankey, from designs courteously placed at their disposal by Lieutenant-Commander Wylie. Certain designs are stronger and lighter than the best spruce or steel tube struts.

FIG. 23.

Fig 23 shows the Birmingham Guild strut No. 4. This was designed to be constructed in two halves, the nose of the strut being designed to take the whole load. This nose was made in high tensile steel with a cross piece of the same material connected by electric spot welding.

The tail fairing was made of aluminium. The joint between the fairing and nose was made with a tinsmith's folded joint well hammered down. This strut weighed complete with end fittings 3 lbs. 1½ ozs., thus bringing the weight below that of the lightest Avro wood strut. On test, it supported a load of .75 tons on 66 inch centres, being 20% stronger than the Avro wood strut of nearest weight,

although the wood in the latter case had a Young's modulus of 1.8×10^6 lbs. per square inch.

FIG. 24.

Fig. 24 shows Birmingham Guild strut No. 5, which is extremely simple in construction. It is composed of three units only, a shell and two diaphragms, the extra one being added in this case to give greater rigidity and strength. The production of this strut required no hand labour. The units are all blanked out and formed up in presses, the units themselves being jigged together for spot welding, and the whole of the electric spot welding being done in three-quarters of an hour. The actual cost of this strut in production is stated to be half that of wood. Its weight is 3.15 lbs. as against 3.25 lbs. for the wood strut. Its failing load on 69 inch ball centres is .77 tons as against .475 tons for the wooden strut.

Struts for Large Machines.

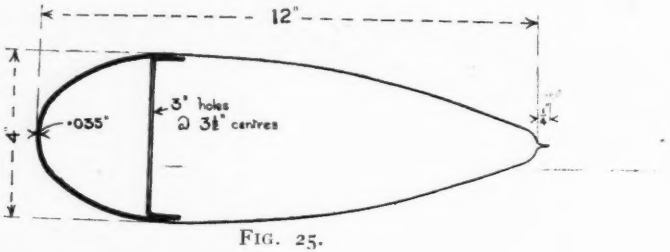


FIG. 25.

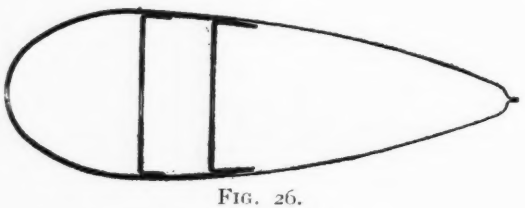


FIG. 26.

Figs. 25 and 26 give outline particulars of two types of streamline metal struts by the Birmingham Guild which are well suited for large machines. The double web type of construction, shown in Fig. 26, gives greater stiffness for a given width and weight when made to a given streamline section, say of 3 to 1, than any other known type made to the same streamline section. It is therefore stronger.

These types of struts are suitable for lengths up to 25ft. or over, and there is no limit to the load they can be designed to carry.

Hollow wooden struts made of grade A spruce are known to be unsuitable for tropical use. Moreover, for a given width, weight and length, hollow wooden

struts have been found to be about 50% heavier than the double strut described above.

A round steel tube with wood and fabric fairing is about 70% heavier than these struts. Apart from this, solid drawn steel tubes of the sizes necessary for the largest machines are unobtainable.

Duralumin Machines. Vickers' Spars.

All the previous descriptions have especially related to steel constructions, but many of the constructions are suitable for duralumin. The problem of the duralumin machine of various types has been tackled successfully by Commander Craven and Messrs. Pratt and Temple, of Vickers, Ltd., starting from a suggested design courteously placed at the firm's disposal by Professor Lea, of Birmingham University.

Methods of Design and Calculation of Guide Spars.

In designing the most economical braced girder to withstand a certain definite system of loading, there are usually three points which have to be considered if the highest efficiency is to be obtained. These are: (*a*) The ratio of the over-all depth of the girder compared with its pin-jointed length. If the girder is made very deep the weight of the bracing becomes excessive, while on the other hand if made too shallow, unnecessary weight has to be put into the main flanges or members. The maximum depth of the girder is usually limited by the section of the plane.

(*b*) The pitch of the bracing. If this is too great, unnecessary weight has to be put into the main flanges. If the pitch is too small the weight of the bracing is unnecessarily heavy.

(*c*) The properties of the actual section used for the main flanges or members. If the member is made very thin it fails at a low stress by secondary flexure, while on the other hand if the flanges are made very thick compared with their width, the radius of gyration for a given sectional area is necessarily small in proportion to the pin-jointed length, *i.e.*, to the pitch of the bracing, and hence the member also fails at a low stress.

The effect of varying each of the above items has been very carefully investigated and general data obtained which enables not only the strength of any particular girder to be accurately calculated, but also the girder to be so proportioned as to allow the maximum efficiency, from the point of view of strength for weight, to be obtained.

In addition to the above three points there is an additional one (*d*) which has been investigated and has been found may be neglected. At first when the subject was approached it was thought that the strength of the small elements between points of attachment of adjacent bracing would depend on the stiffness of the bracing. Experiment has proved that the increase of strength to be obtained by this means unnecessarily increases the weight of the bracing and is not economical, and that the strength of the individual main member or flange may be calculated, by confidential information memoranda 720, as a strut with pivoted ends and of a length equal to that between the centres of the bracing attachment. If the bracing were infinitely stiff and were attached to the main member in an absolutely rigid manner, the pin-jointed length of the elementary strut would be half the pitch of the bracing, on the other hand, if the bracing is without stiffness or if only attached by a single rivet to the main member then the pin-jointed length is taken as equal to the pitch of the bracing. The exact effect of the stiffness of the bracing on the pin-jointed length of the main member can be actually calculated in any case.

C.I.M. 720 has been brought up to date and amplified by a large number of experiments on flanges of various thicknesses.

Having fixed on the dimensions in (*a*), (*b*) and (*c*) above the strength of the girder as a whole is next considered. The strength of the individual member, usually the flange between points of support of the bracing, is taken as the limiting stress at the centre of the girder, and then the failing load at the ends of the girder is calculated by the Alexander strut formula which has been proved to give results in agreement with experiments.

The Alexander strut formula is as follows:—

$$\frac{l^1}{k^1} - \frac{l}{k} = A \frac{\delta}{k} \times \frac{\sqrt{p}}{f - p}$$

where p is the intensity of stress in tons per sq. in. on the ends of the strut at failure.

f is the limiting fibre stress at the centre of the strut at failure. It is approximately equal to the limiting fibre stress under conditions of pure bending.

$\frac{l^1}{k^1}$ is equal to $\pi\sqrt{E/p}$. If Euler's curve for the material is plotted, *i.e.*, $p = \pi^2 E/(l/k)^2$ then l_1/k_1 is equal to the horizontal distance out to this curve at a height corresponding to the failing pressure p.

$\frac{\delta}{k}$ is the ratio of the distance of the extreme fibre from the neutral axis, to the minimum radius of gyration, measured in the direction of the latter.

A is a constant which equals $2c\sqrt{E}$ where c is the ratio of the equivalent eccentricity to the radius of gyration, usually taken as 1/10 for ordinary struts and 1/20 for especially straight struts. The value of $A = 2c\sqrt{E}$ is found by experiment for duralumin braced girders to be about 10.

The thinner the flanges of the angle, that is, the higher the value of s/t, where s equals the thickness of the flange, and t equals the width, the lower is the limiting stress at failure at the centre of the strut. This reduction in the limiting stress in the thinner members is of course due to the effects of failure by secondary flexure.

By plotting the failing loads of a series of experimental beams having varied thickness of angles against s/t for the angles a simple investigation shows the most efficient value of s/t to use with a fixed pitch of bracing.

With plain angles the limiting stress for sections for which $s/t = 30$ is only 7.8 tons per sq. in. On the other hand, for values of $s/t = 7$ the limiting stress is 17.5 tons per sq. in. The most economical values of s/t for plain angles appears to be between 6 and 8 and in any case should not exceed 10.

Large Spar.

A photo of a typical specimen of the series of girders for a large machine built up to investigate the relations of s/t and limiting stress for plain angles is shown in Fig. 27.

A similar series of girders were constructed with a modified section for the main members, as shown in Fig. 28, which is a typical specimen.

In general it was found that lipping improves the thin section, while on the other hand the failing stress in the case of the thicker sections is only a little

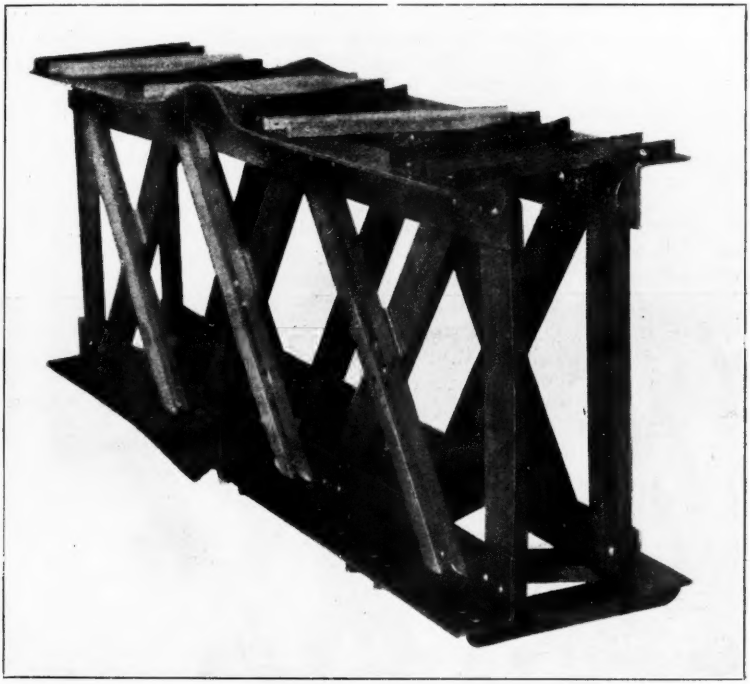


FIG. 27.

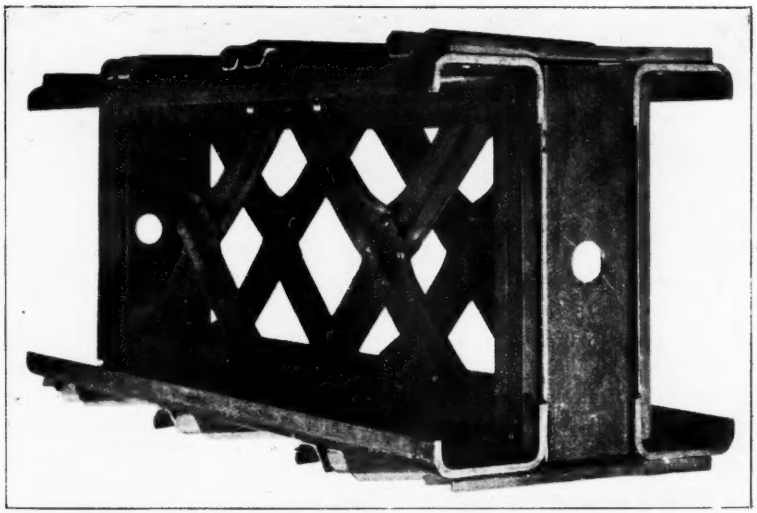


FIG. 28.

higher. For instance, the limiting stress for sections for which $s/t = 30$ is 11.7 tons per sq. inch as against 7.8 for plain angles. Whereas for values of s/t of 7 the limiting stress of the lipped section is only 17.5, *i.e.*, the same as the plain section. Hence there appears to be no advantage in lipping the sections.

In order to obtain the most economical design it is obvious that the dimensions of the main members will require to be varied from place to place. Therefore at the centre of a large machine, in view of the fact that duralumin cannot efficiently be solid drawn in sections thicker than 0.2in., it may be found that the size of the angle members required becomes too great to permit them to be solid drawn. It therefore becomes necessary to modify the design. One such modification is shown in Fig. 29.

FIG. 29.

In this design plain angles are used to which are riveted longitudinally corrugated plates. To prevent local buckling of the plates the pitch of the rivets should not exceed 15 times the thickness of the plate.

With regard to bracing it has been found that the best type of bracing is quite different from that used in airship girders.

In the case of airships, since the shear is small and the main members are of light section with a large pitch for the bracing, it follows that a rigid bracing in the plane of the members is economical. Moreover discontinuous bracing gives a further economy.

In the case of aeroplane girders the main members are much heavier and the value of L/K between bracing points so much smaller that the increase of strength to be gained by providing stiffening bracing is not justified. Moreover, since the

shear is large it follows that the bracing should be practically continuous to obviate the introduction of local bending moment; further, the Zeppelin type of bracing is inadmissible as this would necessitate double bracing.

The problem of the suitable attachment of the fittings presents as great difficulty in the case of large machines as in small ones. It is of such importance that the design should be modified in the first instance to enable this to be done economically.

In calculating the strength of a spar it is necessary to make allowance for the extra stresses induced by the bending moment introduced by deflection. For wooden spars it is usual to use Perry's formula for a strut subjected to a bending moment. The bending moment due to the lateral load is then multiplied by $Pe/(Pe - P)$ to obtain the equivalent bending moment. Where Pe = Euler's crippling load and P = end load in lbs. This makes allowance for the additional stresses placed upon the spar due to the bending moment obtained by the product of end load times the deflection, and gives fairly satisfactory results for spindled wooden spars. It cannot be used, however, for calculating the strength of metal construction, experiment having proved that the deflection is of the order 10 times that given by Perry's formula.

The deflection of metal spars calculated in the following way has been found by Mr. Temple to agree with practice.

From the ordinary theory of beams the deflection in the centre of a girder under side loading is equal to

$$\delta = \frac{5}{48} \frac{L^2 M}{EI}$$

Where δ is the deflection in inches.
L is the length between the supports in inches.
M is the maximum bending moment in inches.
I is the moment of inertia in inch units about an axis perpendicular to the direction of loading.
E is Young's modulus for the material of the girder which as a result of bending tests on girders is taken as 5,500 tons per sq. in.

Since

$$\frac{M}{I} = \frac{2f}{D}$$

where f is the limiting fibre stress and D is the total depth of a symmetrical section we have

$$\delta = \frac{5}{48} \times \frac{L^2}{5{,}500} \times \frac{2f}{D} = \frac{1}{26{,}400} \frac{fL^2}{D}.$$

Now in the case of a long strut, if the direct stress is ignored, practically the same law should hold.

Since

$$M = Pe \times \delta \quad \therefore Pe = \frac{M}{\delta}$$

but

$$Pe = \frac{\pi^2 EI}{L^2}$$

$$\therefore \frac{M}{\delta} = \frac{\pi^2 EI}{L^2}. \quad \therefore \delta = \frac{ML^2}{\pi^2 EI}$$

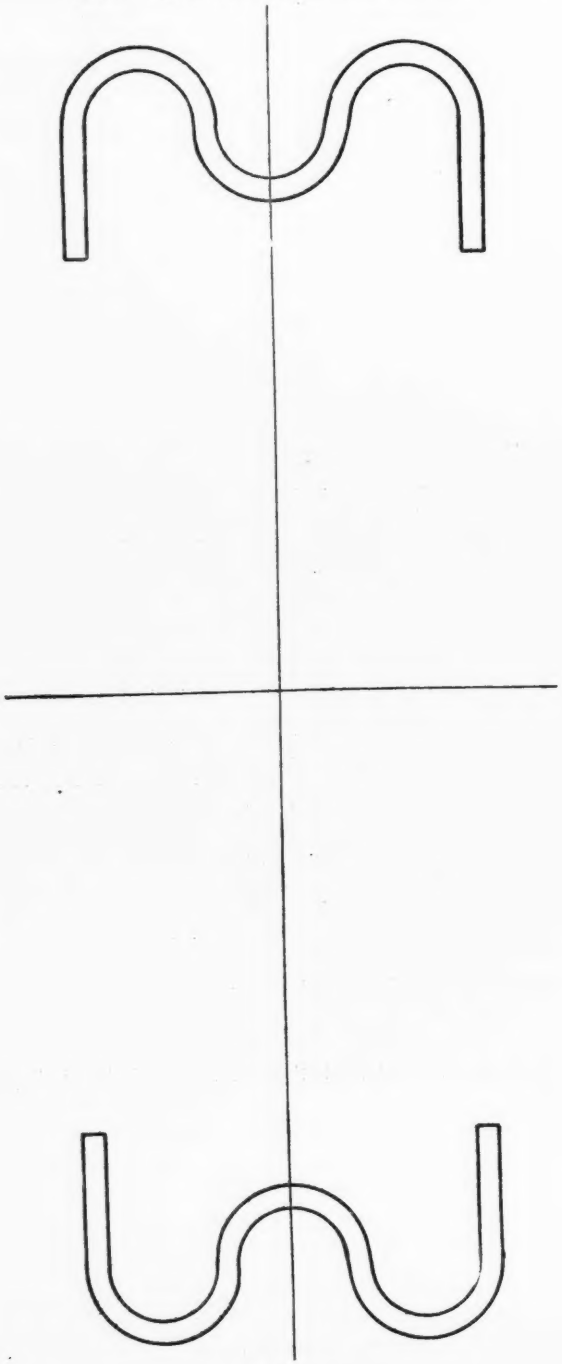


FIG. 30.

but

$$\frac{M}{I} = \frac{2f}{D}. \quad \therefore \delta = \frac{2L^2f}{\pi^2ED} = \frac{2}{9.87 \times 5{,}500} \frac{L^2f}{D}$$

$$\therefore \delta = \frac{1}{27{,}100} \frac{fL^2}{D}$$

The deflections calculated by the above means agree with the results of experiments. Therefore in designing beams to withstand combined stresses the approximate deflection should be calculated by the formula

$$\delta = \frac{1}{26{,}400} \frac{fL^2}{D}$$

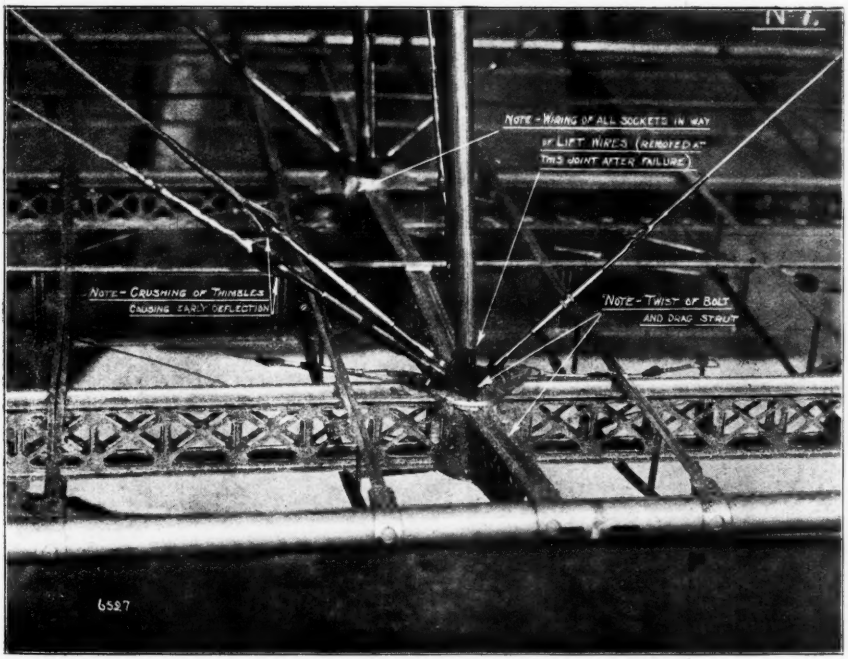

No 1.
NOTE - WIRING OF ALL SOCKETS IN WAY OF LIFT WIRES (REMOVED AT THIS JOINT AFTER FAILURE)
NOTE - CRUSHING OF THIMBLES CAUSING EARLY DEFLECTION
NOTE - TWIST OF BOLT AND DRAG STRUT
6527

FIG. 31.

Intermediate Spar.

In experimenting with metal construction one is impressed with the inconceivable number of designs which are possible. The most suitable design varies with each type of machine and the load which it is to carry.

The duralumin designs previously shown are suitable for a large machine.

In the case of machines of intermediate size, *i.e.*, the order of 10,000 to 12,500 lbs., a suitable type of section is found to be one in which the main members are of channel section, which may be corrugated when necessary to

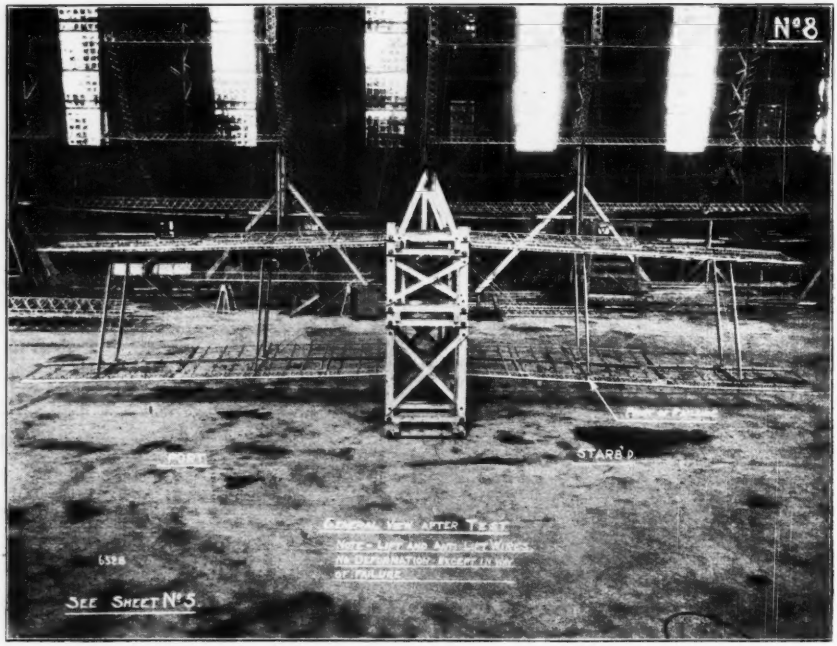

Nº8
STARB'D.
GENERAL VIEW AFTER TEST
NOTE - SLACKNESS OF ANTI-LIFT WIRES.
NO DEFORMATION EXCEPT IN WAY OF FAILURE.
SEE SHEET Nº 5.

FIG. 32.

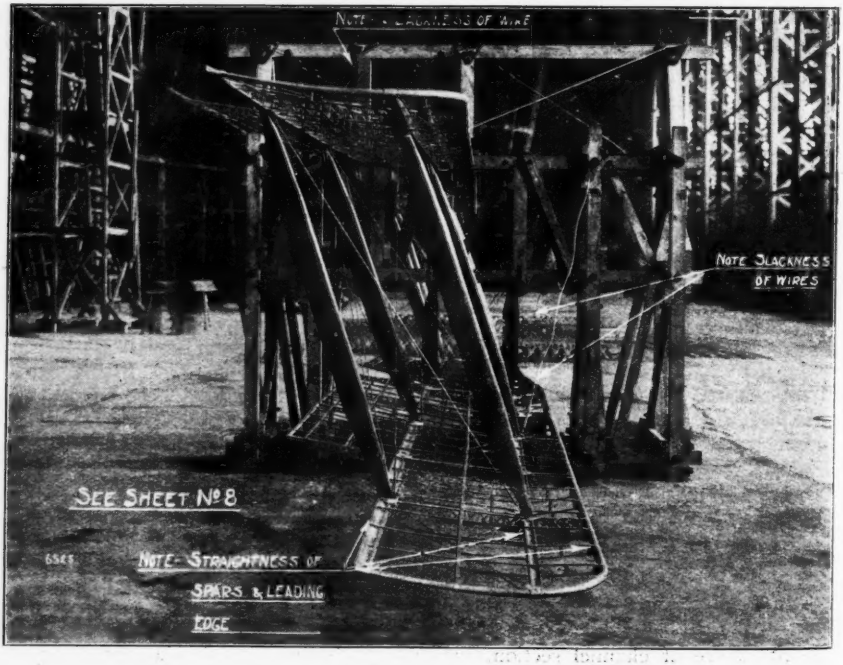

NOTE - SLACKNESS OF WIRE
NOTE SLACKNESS OF WIRES
SEE SHEET Nº 8
NOTE - STRAIGHTNESS OF SPARS & LEADING EDGE

FIG. 33.

reduce the effects of failure by secondary flexure. The actual section as designed is shown in Fig. 30.

With thicker sections the central corrugations may be dispensed with. A spar of this type weighs only 75% of that of a corresponding spruce spar of the same strength.

Small Spar.

A duralumin spar suitable for a small machine, such as the Avro, is shown in Fig. 31.

This was taken after the wing had withstood a load factor of 10.7.

Fig. 32 shows a front view of the whole structure taken after failure.

Fig. 33 shows a side view of the complete wing structure taken immediately after failure.

The excellent way in which this construction has withstood this phenomenal load is clearly shown in the photographs and requires no comment. The large initial deflection on the starboard side was due to the elongation of the brass thimbles fitted to the splicing of the wire bracing which is clearly shown in Fig. 31. This deflection ultimately caused the failure to occur on the starboard side.

Method of Testing Specimens.

In investigating the suitability of a construction to withstand the loads which are to be put upon it care should be taken to reproduce as nearly as possible the conditions under which the specimen will be loaded in practice.

Thus, the specimen should be subjected to the same bending moment and end load as in practice. Reference has heretofore been made as to the serious errors which have been made in testing wooden specimens in pure bending instead of in combined bending and compression. The same errors may be made if the correct procedure is not followed in testing metal construction. In the first experimental stages of metal construction the author was unable to get certain manufacturers to construct specimens longer than three feet. Arrangements were therefore made to test these specimens in shackles, as shown in Fig. 34.

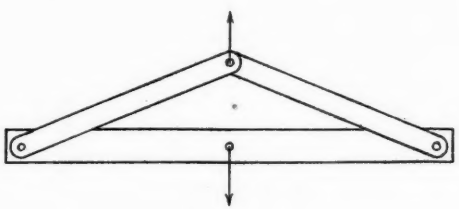


FIG. 34.

The height of the shackle was varied to give the correct proportions of end load to central bending moment.

As soon as circumstances would allow, and suitable designs had been selected from the large numbers tested, arrangements were made for the specimens to be made equal in length to the distance between the points of contraflexure in the actual span. The specimens were then tested as shown in Fig. 35.

The end load L and the bending loads W were applied in the correct ratio until failure occurred.

The bending moment at the centre of the specimen, as is shown in Fig. 36, is the same as in the actual machine. Alternatively to the above the lateral loads W may be dispensed with, providing the end loads L are given the correct amount of eccentricity to provide the necessary bending moment.

Appendix IV. sets forth the results of a few tests on various samples.

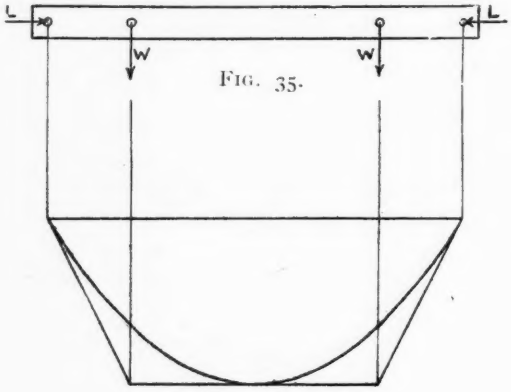


FIG. 35.

FIG. 36.

In presenting the subject of metal construction the author has felt that the problem is too vast to be dealt with as a whole. He has therefore confined himself to a few basic principles and solutions to act as the basis of a discussion.

He feels, however, that metal construction has a great future, and in placing before you a little of the work carried out in the last few strenuous weeks of the war it is hoped that the subject will receive the attention that it deserves from our aeronautical engineers and designers.

All the information now set forth has been obtained from private sources, but before leaving the Technical Department the author took action to place on record a much fuller account. This should now be available. He desires to record his indebtedness to General Weir and the authorities of the Air Ministry for permission to read this paper, and to tender his sincere thanks to his colleague, Major H. Wylie, R.A.F., who has been associated with the author in the development of metal construction throughout the country. He would also like to record his thanks to the various firms with whom he has been associated for their most courteous co-operation and for the ability and energy which they brought into requisition.

APPENDIX I.

Metal Aeroplane Construction.

Thin strip steel of various qualities, having thicknesses ranging from .014in. to .028in. have been experimented with by Messrs. Arthur Lee and Sons, Ltd., Sheffield, for the above.

This has entailed investigations upon a matter of 135 different samples, including the following:—

(1) The influence of cold work upon the physical properties of thin strip;
(2) The influence of "tempering" cold worked thin strips; and
(3) The influence of "tempering" hardened thin strips upon the physical properties.

The attached graphs show the various influences. It was found that alloy steels were of no material benefit over plain carbon steels in the "as cold-worked condition"; the alloy steels requiring to be heat treated in order to bring out their good physical properties and be of any advancement over plain carbon steels.

Thin strips have been obtained and manufactured by us having yield points from 35 to 100 tons per square inch. Not only in carrying out these experiments

CHART No. 1

Influence of Cold Work on the Physical Properties of Thin Strips 300 ft x 3" x .014

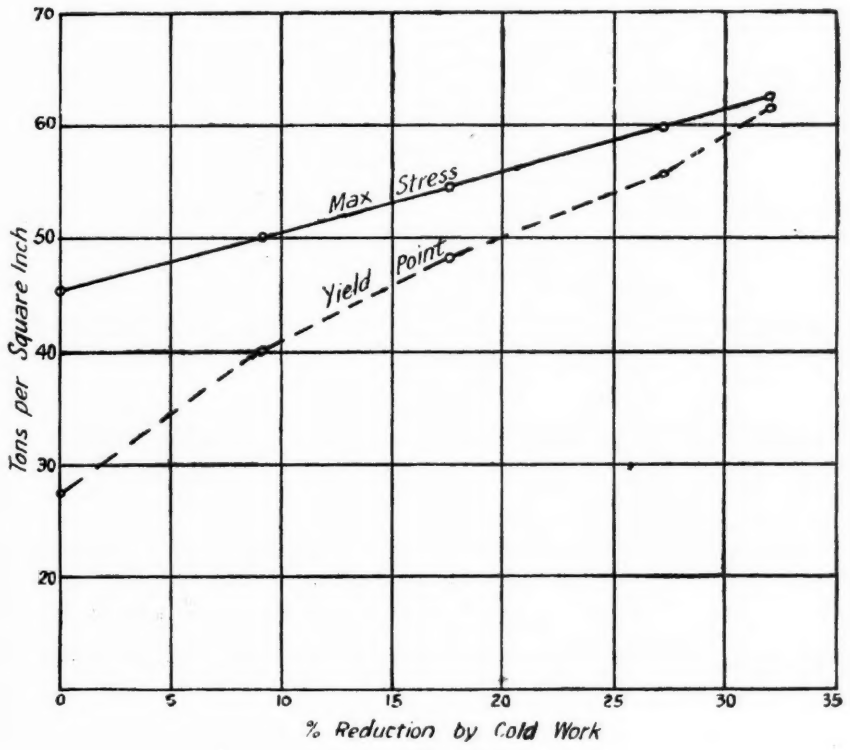


FIG 37.

has this been attained, but we have supplied on a commercial scale the Aeronautical Supplies Dept. and others with several tons of thin steel strips to the 60 ton yield specification in lengths of 300 to 400ft. each.

The following is a short *resumé* of experimental work done by us:—

Cold Worked Steel Strips.

It is found that where strips receive a greater reduction than 40% by cold work after annealing that they are made too brittle.

The breaking stress of the strips is related to the cold work put upon them by the formula $S = 30 + \frac{1}{2}R$.

S = maximum stress, $\frac{1}{2}R$ = half the reduction and is constant.

This formula we find works out very well with strips which do not receive a greater reduction by cold work than 40%, and the following table bears this out, and also that with over 40% the calculated M.S. is too high.

Sample No.	Actual Breaking Stress. Tons per sq. in.	Calculated Breaking Stress from $S = 30 + \frac{1}{2}R$.
0	33.9	$30 + \frac{0}{2} = 30.0$
1	45.5	$30 + \frac{31\frac{1}{2}}{2} = 45.65$
2	50.0	$30 + \frac{49\frac{1}{2}}{2} = 54.62$
3	51.8	$30 + \frac{60.35}{2} = 61.17$
**	30.0	$30 + \frac{0}{2} = 30.0$
4	43.2	$30 + \frac{25}{2} = 42.5$
5	47.0	$30 + \frac{41.75}{2} = 50.87$
**	30.0	$30 + \frac{0}{2} = 30.0$

The following table and Fig. 37 show the influence of cold work on the physical properties :—

INFLUENCE OF COLD WORK ON THE PHYSICAL PROPERTIES OF THIN STRIPS.

LENGTH OF STRIP 300 FT.

Size.	Condition of Strip.	Yield Point. Tons per sq. in.	M.S. Tons per sq. in.	Elongation % on 2in.	Scleroscope Test. Hardness.	Erichsen Value.	Bend Test over radius of 3 times the Thickness.	% Reduction by Cold Work
$3—\frac{1}{8}'' \times .022$	Before cold work	27.2	45.6	11.0	22°	7.00	Good.	None.
$3—\frac{1}{8}'' \times .020$	After cold work	40.0	50.0	10.0	32°	6.80	,,	9.09%
$3—\frac{1}{8}'' \times .018$	,, ,, ,,	47.6	54.25	3.0	38°	6.35	,,	18.18%
$3—\frac{1}{8}'' \times .016$	,, ,, ,,	55.2	59.8	2.5	42°	4.90	,,	27.27%
$3—\frac{1}{8}'' \times .014$	,, ,, ,,	61.2	62.2	2.5	38°	5.00	,,	31.81%

THE INFLUENCE OF TEMPERING ON THE PHYSICAL PROPERTIES OF COLD WORKED THIN STRIPS.

.028 IN. THICK.

Condition of Strip.	Yield Point. Tons per sq. in.	M.S. Tons per sq. in	Elongation % on 2in.	Erichsen Value.	Bend Test over Rod .140" dia. with the Metal.
As cold worked	40.75	40.75	4.0	5.6	Broken.
After tempering at 200° C.	47.25	47.6	2.5	5.36	,,
,, ,, ,, 300° C.	46.5	48.2	4.0	4.23	,,
,, ,, ,, 400° C.	44.6	45.6	6.0	4.72	Good.
,, ,, ,, 500° C.	31.0	36.5	17.0	5.12	,,
,, ,, ,, 600° C.	25.0	31.7	29.5	6.0	,,

See Chart No. 2, Fig. 38.

Influence of Tempering Cold Worked Strips.

The tempering or "blueing" from 0° C. to 400° C. has increased the yield point and maximum stress over the cold worked value, a list of which is given in the preceding table and shown by Chart 2. There appears to be a critical point between 400° and 500° C., where the fall in yield and M.S. occurs, whilst the elongation is greatly increased. The M.S. and yield point does not lower again to that of the original cold worked figures until about 425° C. is reached.

CHART No. 2

The Influence of Tempering on the Physical Properties of cold worked Thin Strips .028" thick

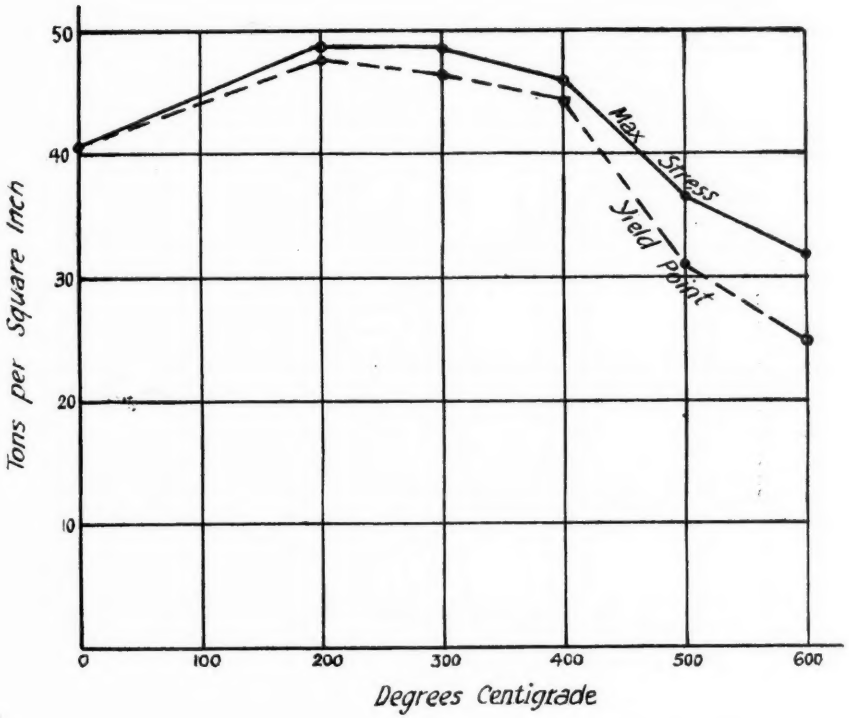


FIG. 38.

This phenomenon is remarkable, but there is no doubt about it, as this has been proved by us many times, it being experienced on tempering all cold worked materials.

The bend tests are not improved by this tempering until over 425° C. is reached.

It may be of interest to mention at this stage that on making tensile tests

on thin strip steels after the yield point has been reached they break in a peculiar manner, diagonally, with V top and bottom and sometimes assume an X, then at the finish break horizontally.

CHART Nº 3

Influence of Tempering Hardened Thin Steel Strips ·028 thick

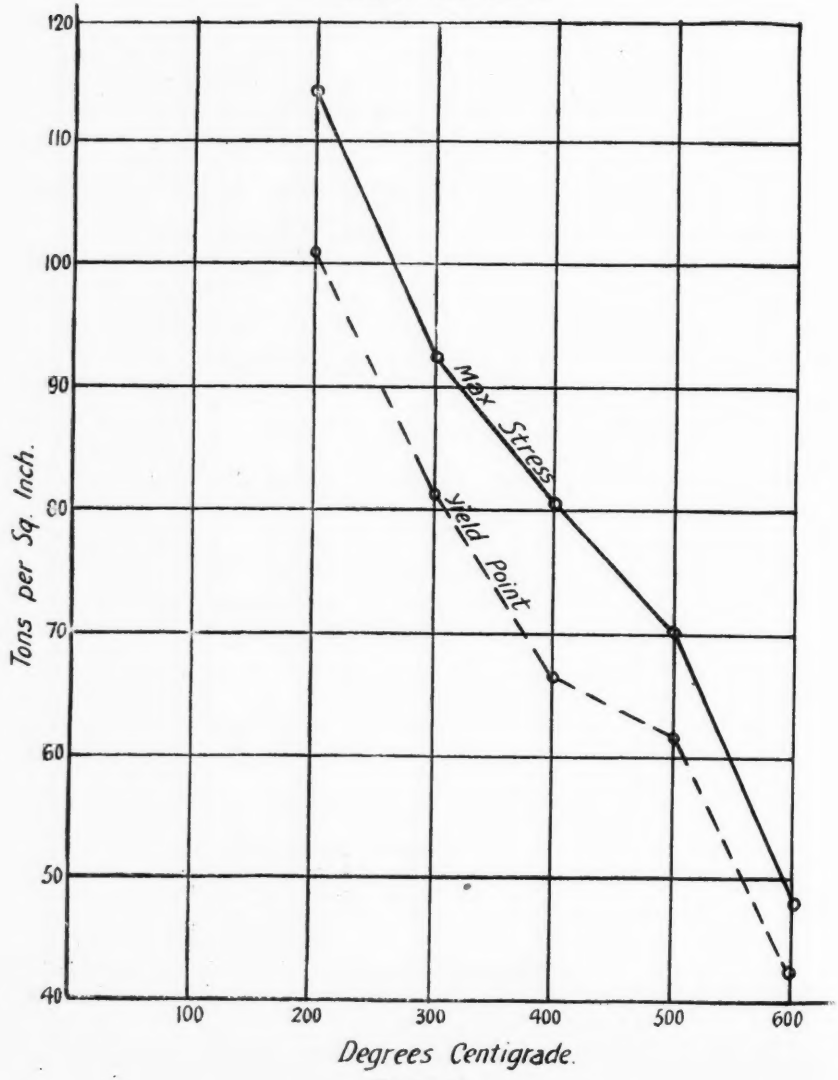


FIG. 39.

The Influence of Tempering Hardened Thin Strips.

Here we get an opposite effect to that which is obtained on tempering cold worked strips. On tempering hardened strips from 0° to 600° the M.S. and yield point are decreased whilst the elongation is gradually increased. The bend tests are improved from 400° to 600° C.

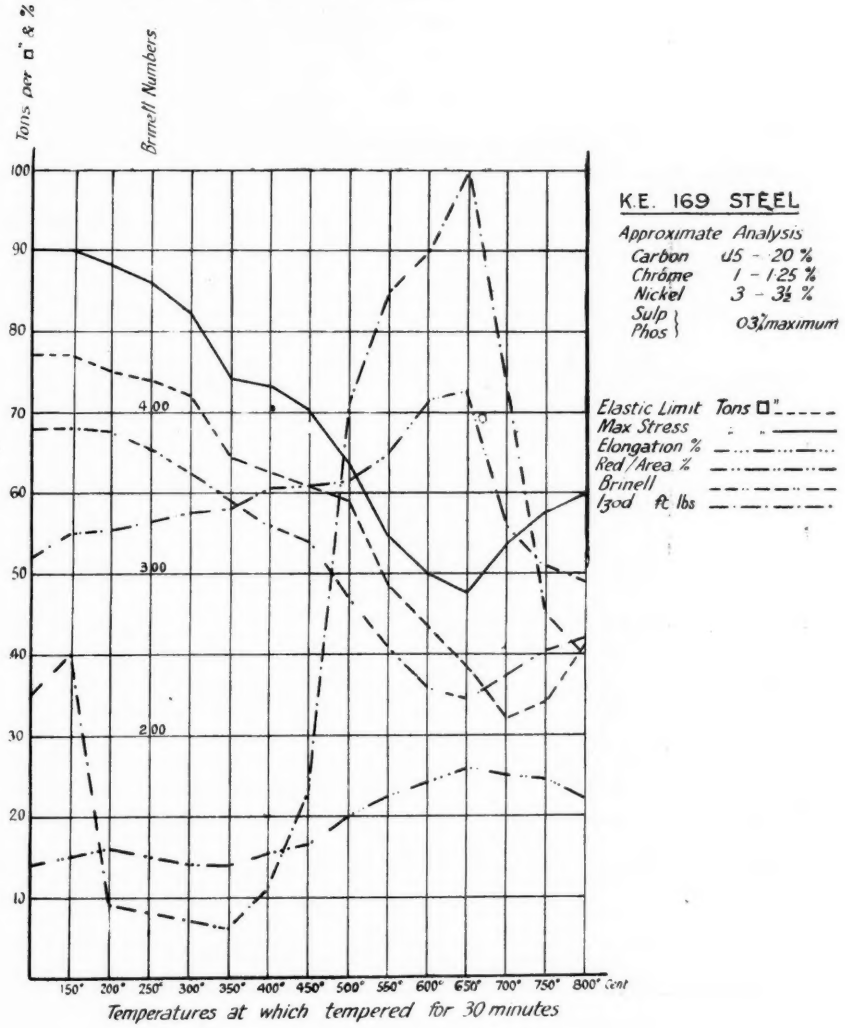


FIG 40.

All bend tests have been made with metal that is lengthwise of the strip.

Hardened Strips Tempered at.	Yield Point. Tons sq. in.	M.S. Tons sq. in.	Elongation % on 2in.	Erichsen Value.	Bend test over 0.140" dia. rod.
200° C.	101.0	114.0	2.5	1.28	Broken.
300° C.	81.8	92.3	3.5	2.80	,,
400° C.	66.8	80.7	6.0	4.60	,,
500° C.	61.4	70.2	9.5	4.62	Good.
600° C.	43.4	48.0	11.0	3.70	,,

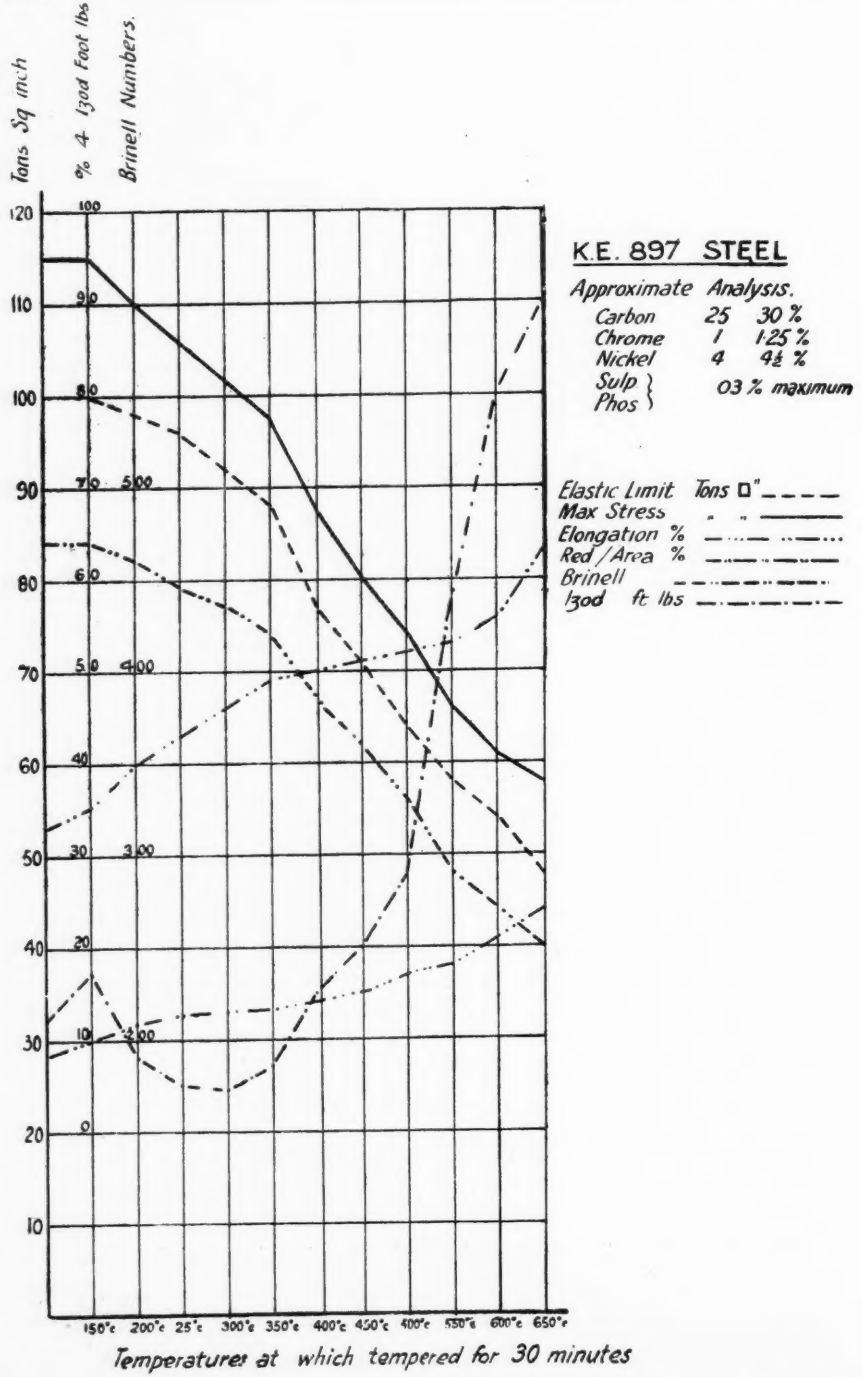

Tons Sq inch
% 4 Izod Foot lbs
Brinell Numbers.
120
110
100
90
80
70
60
50
40
30
20
10
100
90
80
70
60
50
40
30
20
10
0
500
400
300
200
150°c 200°c 25°c 300°c 350°c 400°c 450°c 500°c 550°c 600°c 650°c
K.E. 897 STEEL
Approximate Analysis.
Carbon 25 30 %
Chrome 1 1·25 %
Nickel 4 4½ %
Sulp } 03 % maximum
Phos }
Elastic Limit Tons □"
Max Stress
Elongation %
Red/Area %
Brinell
Izod ft lbs
Temperatures at which tempered for 30 minutes

FIG. 41

APPENDIX II.

The problem before the steel maker may be briefly stated to fall under the following four heads:—

(1) The steel must be one which will give the highest possible tests, especially in regard to the true elastic limit, combined with a considerable ductility.

(2) It must be capable of being worked into the complex shapes required without showing any signs of cracking.

(3) The heat treatment must be of as simple a nature as possible, the temperature range being a fairly wide one.

(4) The material must be regular, so that the minimum tests may be always obtained by standard heat treatment.

It will readily be seen that in the nature of the proposition, a steel must be used which will give the maximum strength for a given weight.

If merely the tensile strength had to be considered there would be no difficulty in producing the necessary material, but, taken in conjunction with the other requirements, the problem does not admit of so ready a solution. Great ductility is also required, as the heat treated sheet or strip which is used in the formation of the spars has to be formed into the necessary section, when in the heat treated condition, and this is necessarily done by cold forming the section in suitably shaped rolls or dies.

Some of the bends are very severe, requiring the strip to fold back upon itself, and as the strip must take this without any signs of cracking, it is obvious that great ductility must be an essential feature of the steel used. This property is also of great importance in those spars where a large amount of riveting is necessary, and as the rivet holes are punched out cold from the heat treated strip, and they must stand this operation without any splitting.

In addition to this the steel must be capable of resisting shock as well as withstanding loads more or less gradually applied.

The tremendous strides made in the building up of spars by welding various members together has made a further and important demand on the qualities of the steels used, and as this method of spar formation seems likely to be of great use, only those steels which weld perfectly will be of any service.

The physical qualities of two steels which have proved highly satisfactory when great strength is required, together with all the other desirable qualities, are seen in the curves illustrated in Figures 40, 41.

It is very often found that good steel is of little commercial value, because the range of temperature for heat treatment is much too narrow, or else the operations are too complicated, especially when dealing with it in the form of thin strip. These limitations are of the greatest importance when the parts into which the material goes do not admit of being easily tested, or when the working up of the parts accentuates any of the errors in the heat treatment.

The steels in question require a heat treatment which admits of a fair range of temperature in hardening, whilst the effect of tempering heats can be readily seen by reference to the curves.

It will be conceded that regularity is of vital importance, as unless minimum tests can be relied on all manner of difficulties will arise, not only in the actual strength of a part, but in the manipulation of the material when formed into shape. These difficulties have all been overcome in the steels in question. There is nothing new claimed in their composition, but the processes involved from the

raw material to the finished strip have been carefully developed, so that every precaution is taken to eliminate sources of trouble.

Tests are carried out after every process from the production of the ingot forward, so that no material is allowed to pass from any one stage of manufacture to another unless it is up to the standard for that particular stage. It is the careful and ceaseless testing of the steel which has had so much to do with its success in steel spar construction.

APPENDIX III.

Ingots after being analysed and tested follow the usual processes of manufacture, viz., forging, hot and cold rolling. After each process the steel is examined and numerous tests are made and analyses are taken. The re-heating for forging and hot rolling and the frequent annealings during the repeated cold rollings require the utmost care and precision to ensure freedom from decarbonisation and other defects produced by incorrect heat treatment. In cold rolling process care must be taken to avoid crushing by over rolling. The strips when finished are in coils of about 300 feet in length, the width up to 5 inches, and thickness generally running between .028in. and .011in., although for making models strip has been supplied as thin as .004in.

After cold rolling the strips are hardened and tempered by special process, in which the temperatures of furnaces and quenching baths are carefully governed by pyrometers, the scale formed in hardening being afterwards removed by a special scouring process. The strip is then finally gauged, tested for tensile strength and bending capacity longitudinally and transversely.

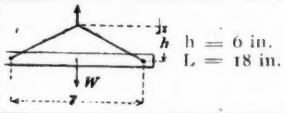
The following tests, with specimens showing examples of bending, illustrate the physical properties of the strip, which is ready for forming into any required section, and is capable of being riveted or welded without further treatment whatever. The steels which have hitherto been used for this purpose are K.E. 169 and K.E. 897.

Number.	Size.	Max. Stress Tensile.	Scleroscope Hardness.	Quality.
1	$4\frac{1}{2}'' \times .015''$	43·5	32	K.E. 169.
2	$3\frac{1}{2}'' \times .022''$	52.2	49	,,
3	$2.88'' \times .004''$	53·5	51	,,
4	$4'' \times .018''$	71.6	59	,,
5	$4'' \times .015''$	75·2	61	,,
6	$3\frac{1}{2}'' \times .018''$	101.3	65	K.E. 897.
7	$1.68'' \times .015''$	103.6	75	,,

APPENDIX IV.

COMBINED BENDING AND END COMPRESSION.

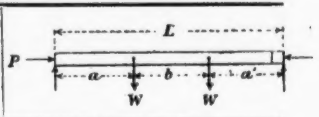
Maker.	Material.	Weight lbs. per foot run.	Load in lbs.		Max. fibre stress due to B.M. & end load. Tons sq. in.	Deflection at centre in inches	Direct tensile stress on material. Tons sq. in.		
			W	P			Yield.	Ultimate.	
Rudge	Steel, K.E. 897	·57	350	6200	69	1.16	50	75-90	$a=10''$, $b=30''$, $L=50''$.
A. V. Roe (Rear Spar)	Wood (Spruce)	·574 to ·752	120	4770	—	1.13			$a=20''$, $L=60''$.
SIMPLE BENDING AND SHEAR.									
Dunlop (Double Spar)	Steel cycle rims clamped together at 5″ centres	—	425	0	54	—	48.5		$a=10''$, $a^1=9\frac{1}{2}''$, $L=29\frac{1}{2}''$.



It will be noted that both the Dunlop and the Rudge Spar develop the full strength of the material since the maximum fibre stress is greater than the yield point of the material. The Dunlop Spar was made by joining two straight pieces of Westwood rim together. The tests prove that the principle of construction is sound. The spar may be cheaply made at the rate of 9 feet per minute by existing machinery.

APPENDIX IV. (*continued*).

COMBINED BENDING AND END COMPRESSION WITH SHACKLE GEAR.

Maker.	Material.	Weight lbs. per foot run.	Central load. lbs. W.	Maximum fibre stress. Tons sq. in.	Direct tensile stress. Tons sq. in.		
					Yield.	Ultimate.	
Vickers, Lea design, Ex. D.3	Duralumin	.421	1008	19.77	17.95	26.95	Tested to required stress only.
Vickers, Rea design, Ex. D.3	Duralumin	.421	1232	24.14	17.95	26.95	Tested to destruction.
Rudge	Steel. Flanges K.E. 169. Webs carbon steel, die hardened and tempered	.52	1270	74	—	—	Failure started in flange part of web. Spar is stronger and lighter than grade A spruce.
Humber	3.5% nickel steel	.8	1028	21.75	30	38.1	Failure by buckling free laps on compression side.
Humber	5% nickel steel	.8	1252	26.56	46	50.1	—
A. V. Roe (Front Spar)	Wood (Spruce)	.514 to .654	1232 to 1568	5950 to 8016 lbs. sq. in.	—	—	All specimens failed on compression side.
A. V. Roe (Rear Spar)	Wood (Spruce)	.574 to .752	952 to 1568	6175 to 9603 lbs. sq. in.	—	—	—

The last two columns relate to wooden specimens of good quality tested under best conditions as to dryness. For comparison with metal the lowest loads supported should be taken and the average weight. The variation of the strength and weight of wood is however so large that the figures so obtained will unduly favour wood.

PROCEEDINGS.

SIXTEENTH MEETING 54th SESSION.

The Sixteenth Meeting of the Session was held on Wednesday, May 14th, 1919, in the Theatre of the Royal Society of Arts, London, General R. K. Bagnall Wild, C.M.G., presiding.

The CHAIRMAN said he thought the first thing they should do was to congratulate Dr. Thurston on his recovery from a very nasty spell of illness. It would be remembered that his lecture was postponed because he was ill, and they were glad to see him back again amongst them. He would now ask Dr. Thurston to read his lecture.

Dr. THURSTON then delivered his lecture, prefacing his remarks with an appreciation of the work of the Royal Flying Corps Hospitals and its honoured founders and paying a tribute to Mr. P. Y. Alexander.

DISCUSSION.

Major A. R. LOW said his remarks could only be general, and not expert, so he would be extremely short. He could not sit down, however, without reminding the Society that Dr. Thurston was the pioneer in aeronautics in that Society. He had started more researches, which were now huge specialities, than any other man there, and the latest was that question of metal construction. He thought he (Major Low) was responsible for the first all-metal machine in this country, and the weight of the wings came out so enormous, with the ordinary tubular steel construction, that they had to scrap them and use spruce. If he had had the methods Dr. Thurston had now exposed he thought he might have got the first all-metal machine into the air. They started by getting 45-ton steel tube of .247 thickness and 1½in. diameter, which was used for the fuselage. The supplies failed, and they could not get British steel manufacturers to guarantee 45 tons. One firm gave them 40 tons, but it was found that unless 37.5 were allowed to pass the inspection they could not get more than 50 per cent. of the necessary supplies. Shortly afterwards he went to Germany, and found they were working with 45-ton steel at half British prices. During the war British steel manufacturers had more than caught up with the Germans, but at that time he pointed out the handicap at which we were working if the Germans could get 45-ton steel in quantities and we could only get 37.5-ton. But Dr. Thurston had shown that steel tube had gone out of date. He suggested that the best results might be obtained by imitating as closely as possible the internal structure of wood. He had been given credit for saying that five tons was the limit that it was possible to put into the air, but he never said that. He said if the structural weights were reduced, the total weight which could be used went up as the square. Dr. Thurston seemed to be aiming to reduce the structural weights to about half, which meant that he would get four times the weight of the present 15-tonners, which were flying successfully. If what Dr. Thurston promised were realised, they might look forward to 60-ton machines.

Mr. H. B. PRATT said he would confine his remarks to the subject of duralumin structures for aeroplanes. If duralumin were correctly treated and handled there was no possibility of corrosion. There had been a widespread impression that it corroded, particularly in the presence of sea water or salt air. His firm's experience on rigid airships showed that corrosion of duralumin was almost negligible, and certainly much less than was experienced with steel—even steel that was protected by enamel or paint of any sort. For equal strength, duralumin had three times the bulk of steel, so that there was three times as much material to withstand corrosion, if there were any, and the loss of strength in the steel would be much more rapid than in the duralumin. The general belief that duralumin corroded was quite unfounded. Duralumin suffered from the difficulty

that girders, spars or struts could only be built up by connecting the members together by riveting, which to some extent imposed limits on the form and design, but experiments were being carried out with spot welding on duralumin, and he thought the results would enable some of those extremely efficient sections Dr. Thurston had shown for steel spars to be adopted, and even better results could probably be obtained with duralumin than with steel. For machines up to four or five tons duralumin was more costly than wood, but with further increase of size the comparison was more favourable, and at 10 tons and upwards duralumin or steel would probably be cheaper than wood, as, in quantity production, the cost of labour for manufacturing spars could be cut down to considerably less than in the case of wood, by the adoption of special processes. As regarded the work they had done at Messrs Vickers, Ltd., he wished to state that they were extremely indebted to Dr. Thurston and Professor Lea for having placed in their hands the information which formed the basis of their experimental work.

Major WYLIE said Dr. Thurston and he always thought differently about flexibility. He thought it was better for a spar to bend and then spring back, but Dr. Thurston thought it was an advantage of the steel construction that it was not flexible. As a matter of fact a spar of very high tension steel would, with a given load, bend a little more than a wooden spar before it broke, and that was a great advantage. Dr. Thurston referred to a machine that flew at an angle of one degree, and said that, owing to the deflection of the wood, the angle of incidence was one degree + two and a half degrees. If a steel spar deflected more than a wooden spar it would decrease the angle of incidence. His experience with regard to the steel used in those struts was that 13,600 was a top figure for the value of E. 12,500 tons per square inch was the usual figure, but it was 12,800 tons in those big Birmingham Guild struts, and for a special kind of steel strip made by Messrs. Arthur Lee & Sons it worked out to about 13,500 tons, but that was not much use at present. His impression was that with duralumin it was 4,500, not 5,500. The Birmingham Guild strut 11ft. long, and of the same section and thickness as the steel, would weigh about 10½lbs., and if the value of E for duralumin was 5,500 tons it would be for wood 2.7 tons per square inch, or if it were 4,500 tons for duralumin it would be 2.2 tons for wood. He suggested that Messrs. Vickers should construct one of those struts. The original spars that were tested were 50 to 60 per cent. stronger than the wood spars, which were of good quality spruce. They failed with a stress of 70 tons per square inch, and the Boulton & Paul spar at 55 tons per square inch. The modulus of section was the same. He found it difficult to believe that the Boulton spar was 70 per cent. stronger than wood.

Mr. PRATT said an explanation was necessary of the figures given in Dr. Thurston's lecture for the value of Young's modulus for duralumin. The value of this, taken from tension tests in solid bars on members, lay between 4,700 tons and 5,000. The figure given in the lecture was obtained from bending tests, and the spars or girders tested for bending were built up with longitudinal top and bottom members connected by bracing pieces. In those cases the value of E given in Dr. Thurston's lecture was deduced from the deflection of the spar, measured from the bending test, and the actual deflection included a certain amount of deflection due to the stresses in the bracing as well as in the longitudinal members. So that the figures of 5,500 tons had to be taken as a kind of virtual E for designing members to withstand bending, which gave correct results in designing spars or members subjected to bending, but if the members were designed purely to stand compression it was correct to take 4,700 tons.

Dr. W. H. HATFIELD said that he thought it was about two years ago since Dr. Thurston came to Sheffield with a determination to produce steel spars. It was not as then completely established that the production of the steel spars was practicable, and at any rate the material was not then available which Dr. Thurston had been putting before them that evening. The enthusiasm Dr. Thurston created amongst the Sheffield people had done much to facilitate a right

solution of the problem. An aeroplane, he took it, was subjected to a great range of temperatures, particularly in some of the colder and hotter climates. Even in this country in cold weather, when planes were flying at very high altitudes, very low temperatures obtained, and in considering the relative merits of the different materials their behaviour at those temperatures must form the subject for serious consideration. In their laboratory he was doing a good deal of work in that direction at the present time.

Dr. THURSTON: You can expect to meet with temperatures in the air up to — 30 degrees. What is the effect, if any, of those temperatures on the various properties of steel? I think steel scores heavily over wood.

Dr. HATFIELD (continuing) said that as regards the case of steel, that was so, but as regards duralumin he thought investigations were necessary. Duralumin was a very useful material, and he was interested to know whether Dr. Thurston had information showing the comparative values of these two materials at low temperatures such as those mentioned. It was now definitely established that steel might be taken to lower temperatures than those mentioned by Dr. Thurston with safety, and that the result was a substantial increase in the maximum stress and yield with a proportional fall in the ductility, but the fall in the ductility was not sufficient to form a danger. Duralumin had a low melting point, and he would be interested to know how far it was susceptible as regards mechanical properties at low temperatures, and he considered that the matter should be immediately gone into. Mr. Pratt compared duralumin with steel from the rustless point of view. He presumed he was not including the 12/14 per cent. chrome steel.

Mr. PRATT: No, I did not compare it with rustless.

Dr. HATFIELD (continuing): Suitable materials produced from this high chrome steel would, no doubt, be forthcoming shortly, possibly sooner than was anticipated. Dr. Thurston said "With mild steel small local damage causes local failure, whereas with higher grade steel local damage is of little importance." He (Dr. Hatfield) thought the analogy between a bridge and a spar would hold fairly good. Small imperfections of technique would almost inevitably always be present, frequently producing high local stress, and he thought that it was imperative to have sufficient ductility to permit of those stresses being dealt with by actual local deformation on the material. Had Dr. Thurston's experiments sufficiently satisfied him that 100-ton material would permit of sufficient deformation from this point of view? He would further like to know which of the spars they had actually had before them to-night had been used in actual flying. Had they actually seen service conditions with that high-tensile material or was the information before them largely of a laboratory kind? He considered that there was now no question at all with regard to the fact that ultimately all our large machines and no doubt small ones would be constructed of metal, and with all-metal structures several very considerable advantages would be obtained. He had studied, with much interest, the two appendices relating to the production of steel for this purpose, and would like to congratulate Dr. Thurston and the investigators who had been responsible for the work. Several of the items of data brought forward were definite contributions to metallurgy. In one portion of the paper Dr. Thurston states that the process of rolling develops a grain in the material which cannot be removed even by complete annealing. He (Dr. Hatfield) was not quite clear as to what was meant by this. Certainly the non-metallic inclusions present would receive an orientation due to the plastic deformation of the material, but apart from that any crystalline arrangement of the metal itself could certainly, in his opinion, be modified by heat-treatment. He noticed under duralumin that Dr. Thurston claimed that duralumin, if properly varnished, is not affected by corrosion under ordinary service conditions. Was Dr. Thurston doing justice to duralumin, because as a matter of fact any metal, properly varnished, would presumably be satisfactory under those conditions? If the author had any information relative to the resistance of duralumin to corrosive

conditions it would certainly be of interest. Under the heading " Dunlop Spars " mention was made of the utilisation of " spot " or " strip " welding. He was of the opinion that welding of any kind should be avoided if at all possible. In conclusion, he considered that the paper would become classical in the technical history of the aeroplane, and was sure had been much appreciated by everyone present.

Mr. DERMOT MOONEY : Although there is no question that some of the designs shown by the lecturer are extremely good on mechanical test as spars, yet so far as is known these spars have never yet been built into a complete wing (metal). Those which he referred to in his lecture, I think I am right in saying, are composite wings, *i.e.*, the spars alone are of steel, the rest of the structure being of wood. At an early stage (August, 1917) we considered, made, and patented designs for a tubular form of boom, but these were put aside owing to the difficulties which such a form of boom presented with respect to the erection of the complete wing of metal. These difficulties are connected with the attachment of the ribs, of which there are a great number, to the spars in a cheap and effective manner; therefore all our spars have the booms designed not only for strength and lightness, but also with a view to the attachment of the ribs by means of the very simple saddle plates which we use, which at the same time ensure that the aerofoil section is correct. Incidentally this method of construction also enables us to effectively erect the ribs in such a way that for any local damage new ribs can be inserted without pulling the whole structure to pieces. Although we have produced all-steel wings which give a factor of safety higher than is required we are still progressing, and with slight modifications of design we are convinced that a spar could be designed which will be quite as theoretically efficient as the good designs which have been shown to-night, and which will still have the practical properties which enable the ribs to be attached to the wing in the simple manner which we now employ. It might be interesting to record that owing to the very simple methods which are possible in metal construction a complete all-steel wing has been erected by two girls without skilled supervision in a time which will compare favourably with that required for the erection of wooden wings. The all-steel wings manufactured by our firm have not only been statically tested with excellent results, but they have been tested in flight and given the most severe tests under these conditions.

I gather from the lecturer's remarks that he thinks it will be some 10 years before metal construction reaches the stage it would have reached in as many months had the war now fortunately ended continued. I do not agree with that view, because the type of wing which I have referred to as made by my firm has already been flown and subjected to every possible stunt known to an expert pilot. In fact, I assume that these are the wings to which the lecturer has referred, because, so far as we know, we are not only the first firm to have metal wings of this type statically tested for up load, but we are also, up to the moment, the first firm to have such wings tried under flight conditions. In fact, it may be interesting as part of the history of the progress of metal construction on the system of which the lecturer has spoken to-night that more than a year ago my firm designed, made, and supplied the wings for the " Bristol " all-metal machine which has lately been frequently illustrated in the technical Press. During the past year this machine has been flown many miles, and has given completely satisfactory results. All-metal aeroplane construction is therefore, in my view, which is based on the practical experience of my firm, working for several years on this type of construction, during which time it has produced wings in steel not only for the Avro, but for several other types of machine, a practical commercial proposition. I think, too, that such of us as have had experience of tropical weather conditions will agree that the transcontinental and transoceanic machine destined for, say, a voyage from England to Australia will have to be of metal if it is to be a practical proposition, and that it will be a practical proposition I have personally no doubt whatever.

Mr. NORTH said the work that had been done on metal spars was largely due to Dr. Thurston and the assistance received from Major Wylie. It blossomed under the sun of official approval and was assisted by a shower—or a gentle dew—of gold. He hoped the necessary assistance would be forthcoming to enable the experiments to be continued. Major Wylie appeared to have access to information regarding Boulton & Paul spars that they had not got. He said the section modulus was the same as theirs. In the tests the strength developed in the flange was 60 tons per square inch. Major Wylie must have been referring to earlier tests on less efficient spars. Otherwise the statement made by Dr. Thurston was accurate.

The CHAIRMAN said the lecturer referred to local damage being a minor matter in the alloy steels. Did that mean a dent one's finger could be laid in or a small hair mark such as a tool mark? From his experience he would think a hair line would have a greater effect on the alloy steel. He was glad the lecturer had laid stress on the danger of relying on the simple bending test as an indication of what had to be withstood in the air. Had stress reversals or vibration tests been carried out on these struts and spars? The vibration test was of great value when considering designs. It was true that with carbon steel there was a wider range for heat treatment than with alloy steels, but during the war the users of steel had learnt to work with the alloy steels within those fine temperature ranges. They had learnt to use pyrometers and so forth, and there was not the danger in using alloy steel that there was a year ago. He agreed that the temperature range from 150 to 450 degrees was a rather wide one.

Dr. THURSTON, replying to the discussion, said he would like to reply at considerable length, but would rather ask questions. He was honoured by a most distinguished and influential audience, and a vast mine of information was gathered together in his audience from all parts of the kingdom. He would have liked to have got some of it. With regard to local damage, he did not mean either hair-pin marks or large dents, but small dents which caused the soft stuff to fail, but not the hard stuff. He had requested that every metal machine during sand test should be subjected to a vibration test, and he thought this had been carried out. It was carried out during the war. He agreed that the temperature range was rather a wide one. It was at least on the safe side, as will be seen in Figs. 40 and 41. He thought that experience will show that a narrower temperature range could be safely used, but in the early stages it was not thought desirable to take risks. He thanked the Chairman and Dr. Hatfield for calling attention to this point. The composition was also given in the paper. He agreed with Mr. Pratt that it would be unwise to say metal construction should be turned down on account of its present cost. Steel work would cheapen, and riveting, which was now done laboriously by hand, would be done by an automatic machine which was now being evolved. Major Wylie had called attention to the important point that a steel structure could be loaded nearly up to the failing load without great deflection and then it stretched like elastic before breaking. It meant that the steel absorbed a lot of energy without breaking. With regard to the deflection of the wings under load, if there were a big deflection in the middle of the wing with increased angle of incidence a lot more had to be lifted in the middle of the span and the structure as a whole was not so efficient as a more rigid structure. His values for E were calculated from bending tests rather than from other methods. They varied from 11,000 tons to 13,600 tons with steel, and with duralumin from 4,500 to 5,500 tons; 5,500 was the figure to be used in calculations of the strength of a spar. He would like to exchange information with Dr. Hatfield with regard to recent experiments, and he would like to see experiments made on the effects of difference of temperature as regarded the properties of duralumin and steel. With regard to the point Dr. Hatfield raised on local failure, if the metal were soft a blow would make a dent, but if it were hard it could be flattened and would spring back. Errors of workmanship were another matter, and it was necessary to have means of distributing pressure at the ends

of the spars and points of attachment of fittings. The fittings which had been evolved did distribute the pressure and no serious defects had been found. Referring to Mr. Mooney's remarks, he pointed out that the statement questioned referred to machines in action in France, and not to machines constructed and not flown. An all-metal machine had been constructed in the Midlands for a naval officer several years before the war and all-metal machines were exhibited at the first aero show in this country in 1909, one being made by Major Low. He congratulated Mr. Mooney on the great improvements recently made in his spars as the result of incorporating suggestions placed at his disposal by members of the Technical Department. With regard to the machine stated to have a load factor of 9.5, he would like to know the weight of this spar in comparison with that of a wooden one, grade A spruce of the same strength in steel. He regretted that he had not been given permission to describe Mr. Mooney's experiments in the lecture.

The CHAIRMAN said the Paper would, he thought, be the parent of many Papers on similar lines and following up the ideas Dr. Thurston had given them. He proposed a hearty vote of thanks to Dr. Thurston for his most valuable contribution to the records of the Society.

Major-General R. M. RUCK, R.E. (President of the Society) moved a vote of thanks to General Bagnall Wild for presiding. He was an old brother officer, and he would spare him a list of the very excellent things he might have said of him, but the work he had done during the war had been extremely valuable and of great national importance. He also expressed the appreciation of the Council of the excellent lecture and discussion they had had, and the good attendance, both in quantity and quality.

ABSTRACTS.

Abstract of paper appearing in "Engineering," September 19th, 1919, by M. A. S. Riach, entitled, "A Complete Theory of the Screw Propeller Working in Air."

The modern theory of the screw propeller, particularly the airscrew developed by the author, is employed in an attempt to generalise the conditions in order to produce a simplification of the method when applied to problems in the design of airscrews. The usual procedure, in commencing the design of an airscrew to satisfy given conditions, of arbitrarily choosing values for the angles of attack of the individual blade elements, is discarded as involving too much statistical labour in favour of the new process described in the paper. This new process consists in so arranging the disposition of the blade sections, chord blade widths, and angles of attack, along the blade length that the final slip velocity at all radii becomes a constant quantity. This immediately results in a great simplification of the analytical work necessary and enables the complete design of any airscrew to be generalised, so that in any design the whole of the work of computation usually necessary may be avoided, its place being taken by a few graphs from which the required airscrew characteristics may be at once read off. At the same time the efficiency of an airscrew, designed to fulfil any set of conditions, is immediately to hand with the result that the best type may be selected, giving greatest economy in any case. The main analysis of the paper is at the outset concerned with obtaining a sufficiently approximate relation between the variable horse-power, density, airscrew diameter, flight velocity, and engine revolutions. For this purpose it is necessary to allow for the aerodynamical "drag" losses on the propeller blades. This is obtained to a sufficiently close approximation and constitutes a correction on the older methods of assessment. Incidentally the analysis throws some light upon the problems of the ventilating fan and direct lift flying machine. The method is quite general and may be applied to methods of assessment other than those adopted by the author in his paper.